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Geotechnical characterization of foamglass aggregate

La caractérisation géotéchnique du granulat de mousse de verre

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ABSTRACT: Ever tightening enviromental regulations for buildings constantly increase insulation requirements. The newest standard, which took affect on January 1st 2018 in Hungary now impose such high thermal insulation specifications, that the floor slabs of large, industrial building must be insulated as well. This promted the need for a material, which can both efficiently insulate the building, while providing a strong enough base for the floor slab. A bearing capacity (E_2) of 70 – 120 MPa can be considered normal for the sub-grade layer for a storage facilty, which decreases significantly if a styrofoam layer is placed on top of it. Foamglass has the potential to solve this issue, while having several other beneficial properties as well, thus being an advantageous alternative to XPS tables. As part of an extensive research project, we conducted a complex test programme to determine not only the bearing capacity of foamglass aggregate but also it's deformation characteristics under both static and dynamic loading. Evaluation of these results allowed us to characterize the material and provide guidelines for its utilization as a subgrade layer.

RÉSUMÉ: Les régulations de plus en plus strictes font sans cesse augmenter les exigences de l'insulation. Le nouveau standard qui est entré en vigueur le 1 Janvier 2018 impose maintenant des spécifications strictes selon lesquelles les dalles de fondation des grands bâtiments aussi doivent êtres isolées. Cela avait pour conséquence la nécessité d'une matière qui peut éffectivement isoler le bâtiment en fournissant d'une strate assez forte pour la dalle de fondation. Pour une couche de fondation d'une facilité de stockage la valeur de la capacité portante (E2) considirée comme normale varie entre 70 – 120 MPa. Cette capacité portante baisse considérablement si une couche de polystyrène est placée au-dessus. Le granulat de mousse de verre a le potentiel de résoudre ce problème en ayant d'autres avantages aussi, grâce auxquels il serait une alternative favorable du polystyrène. Comme une partie d'un projet de recherche étendu, nous avons mené un programme de test afin de déterminer non seulement la capacité portante du granulat de mousse de verre, mais ses caractéristiques de déformation sous l'effet des charges statiques et dynamique. L'évaluation de ces résultats permet de caractériser la matière et fournit des lignes directrices pour son utilisation comme une couche de fondation.

Keywords: geocell; foamglass; insulation; industrial floor

1 INTRODUCTION

As energy efficiency and sustainability are becoming more important factors in the construction industry, foamglass became an interesting alternative to traditional insulation materials. Although foamglass has been around for several decades, it's main use was in the form of panels as an insulation material. It's use as in granular form became more prominent in recent years.

As an aggregate, foamglass is handled during construction as any other granular material would be. Proper parameters must be defined for both construction method and quality control. This prompts the need to be able to define material properties and assign traditional geotechnical parameters - such as compression module, bearing capacity, etc. - to it as well. Currently the use of foamglass aggregate is based on large scale tests and previous experience. This makes the introduction of foamglass aggregate into areas where there is no prior experience with it difficult as there are no set parameters for design. This is further complicated by the fact, that as an artificial material, the properties of foamglass can be altered to better suit one purpose or another.

The introduction of foamglass into the Hungarian market immediately showed, that characterizing foamglass aggregate as a granular materials using traditional geotechnical test is neigh on impossible due to the nature of the material. We have teamed up with the manufacturer to develop a comprehensive testing program both laboratory and field testing to properly characterize the material. The study covered both the material itself and it's aggregate form to better understand how the specific form of the aggregate influences the behaviour.

2 ABOUT FOAMGLASS AGGREGATE

Although foamglass has been around for nearly a century, its use as an aggregate dates back only a few decades, becoming more prominent in recent years.

The manufacture of foamglass aggregate is similar to foamglass blocks. The main ingrident is recycled glass, to which some kind of gassing agent is added to create the cellurar structure of foamglass (Jamidula et al, 2008.). Additional ingridients can be added to modify mechanical properites of foamglass, such as iron tailings (Yin et al, 2016.; Guo et al, 2010.). These ingridients are milled togeather to create a fine powder, which is then baked in an oven to create foamglass panels. The baking temperatures and time significantly influence material properties of the finished product. The main difference when creating foamglass aggregate to foamglass panels is, that the product receives a temperature shock, to create internal stresses. These internal stresses help later on to shatter the panels into aggregate.

Foamglass aggregate is not typically sieved or cruched to create fractions, and as such, it does not have a fixed grain size distribution.

Although references to tests conducted on foamglass aggregate in Switzerland in the 1980's were found, the authors could not find any reliable source for these tests. An extensive testing program conducted by the Norwegian Road Authority (Statens vegvesen, 2007; Leif E., Jörgen H., 2007) was the starting point for the manufacturer of the product and thus served as the starting point for our research programme.

Although there are a number of studies regarding foamglass use in road and embankment construction (T. Dettenborn et al, 2016; Tor E. F., Roald A.), correlating these studies is complex, due to the different materials, construction and compressive methods, site properties, etc. Another issue was, that the purpose of the foamglass aggregate could be different.

Uses of foamglass can namely broken down into three main categories: thermal insulation, lightwight aggregate and secondary aggregate. Use as thermal insulation can be used to decrease ground frost under roads, serve as insulation around pipelines or under/around foudations for buildings.

Foamglass as lightweight aggregate can be used widely in geotechnics, from fill behind retaining walls or bridgeheads to decrease earth pressures, as lightweight fill to lessen load on soft soil, thereby reducing consolidation or subsoil failure, to light fills above and/or structures.

If used as secondary aggregate, foamglass has the advatage, that it is inert, thereby allowing it to be used under any enviromental circumstances. Replacing primary aggregates can help reduce our dependence on primary sources thus slahsing environmental footprint (Zhang 2016.).

Depending on the intended usage of foamglass, the different manufacturers characterize their products based on different standards, making comparisons of these products challanging.

3 TEST PROGRAM

Since the foamglass tested in our research program has been developed by a Hungrian company from scratch (both composition and manufacturing process are new), we could not rely on parameters of other competitors products (Miaspor, Hasopor, etc.), therefore the testing program was set up as such, that all relevant material properties could be determined for its target application and that reliable parameters could be extracted for later studies.

As the main goal of the manufacturer was to use foamglass as thermal insulation under industrial floor slabs, the testing programme focused on its compressability, bearing capacity and workability.

The comprehensive test programme comprised of three levels, corresponding to the different material stages itself. The first was a small scale test of the material itself. For this, special samples were prepared and tested in the laboratory. The second stage was to test the aggregate under laboratory conditions. This proved a bit more complicated, as the its made up of mainly 16-64 mm diameter particles. The third phase focused on the workability of material and the effects on various installation technologies on its bearing capacity and deformation characteristics on site. This large scale test was a full-scale installation and compaction experiment, where over 500 m3 of material was used.

Under laboratory circumstances all tests were performed at least on three different samples, with more complex and significant tests having 10 or more samples to create a statistically significant sample size. This principle was followed during field testing as well, given the limitations of the site.

We'd like to focus on the compressibility of the aggregate sample and the correlation between uniaxial testing of the material.

3.1 Material testing

The first, and smallest stage of the testing programme was to determine basic properties of the foamglass material itself. Although foamglass can easily be poured into comlex forms, that is requires a different heating pattern to foamglass aggregate. Since the production process of foamglass aggregate involves a thermal shock, creating a differenct pattern would alter the thermal curve and thus material properties. This required us to create small scale samples from larger foamglass aggregate particles. These, although up to 100 mm in size, could only be fabricated into roughly 20-30 mm prisms due to their irregular shape (Figure 1.).

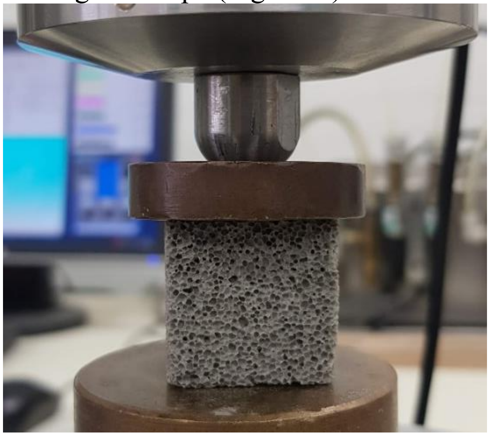

Figure 1. Foamglass material sample under uniaxial loading

The samples were tested for compression, uniaxial loading and dynamic loading. Compression tests were conducted up to 500 kPa stress in an unconfined manner, meaning that the tests yielded the materials Young's modulus (E) not its oedometric compression module (Eoed). This is an important distinction when comparing test results with other material samples and the tests conducted at different material scale.

More significant were the uniaxial compression tests, where the samples were tested using constant displacement speed (0,01 mm/min) until failiure or 20% deformation was reached. A number of tests samples failed due to excessive deformations, because of small imperfections in sample preparation. Samples which failed under loading always did so due to transverse loading. The failiure plane in these cases was almost vertical and through the middle of the sample. Aggregated results of the uniaxial compression tests can be seen on Figure 2. (the solid blue line shows the average test results, while the two dashed lines show the scatter of the results. The two red lines were fitted on the elastic and plastic sections of the curve). Two distinct sections were discernable on the graph. The first is a stiff and elastic section up to ~1,2% relative deformation and 1200 kPa uniaxial stress. This means, that the material has a very stiff elastic behaviour, its Young's module is roughly 100 MPa. The second, plastic section is significantly softer with only 4 MPa stiffness. This means that the core, intact material of foamglass is as strong as weak rock material. Dynamic testing of the samples was done at 75 – 250 kPa stress at 1000 cycles. The load cycle was 1 s, with no load in extension. Samples did not fail during testing, so we were able to determine dynamic and elastic stiffness for the differenc stress levels from these tests.

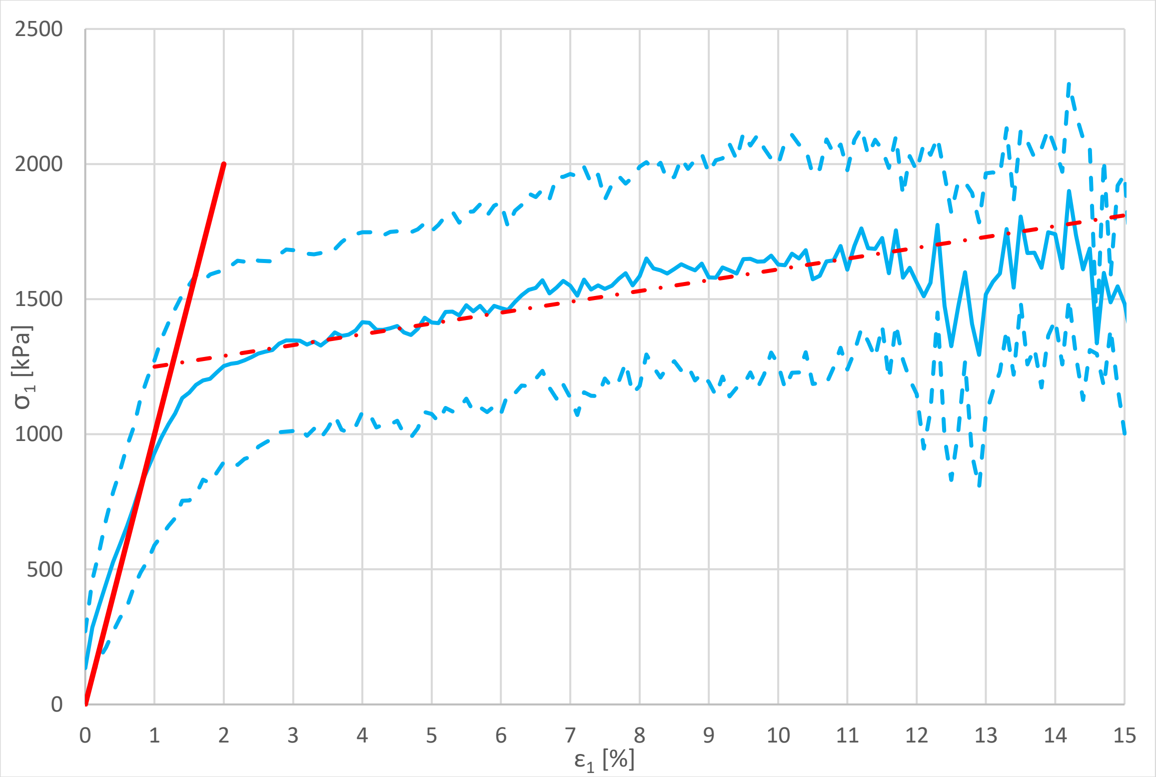

Figure 2. Foamglass material sample uniaxial loading test results

3.2 Aggregate testing

Following the testing of the material of foamglass we moved on to test the aggregate form of foamglass under laboratory conditions. This immidiately posed the difficulty of testing a granular material where particles have 16-64 mm diameter. Testing this material in conventional geotechnical apparatus is impractical as the single particle could exceed the normal sample size. Therefore we constructed a special test frame specially for large particle granular material testing. This was a 300 mm diameter, 250 mm high sample container, which fulfilled the suggested 5D (largest particle diameter) size rule.

The second difficulty was preparing the samples. This was done using a heavy load plate and a vibrating table used for concrete compaction to simulate on-site compation. The aim was to achive the 1:1,3-1,4 ratio suggested by the manufacturer without damaging the material with excessive loading. Despite our best efforst to compact the material samples, we could not achive a perfectly flat surface, due to the size of the individual particles. This in turn caused the load plate to transfer loads on distinct points, rather than uniformly significantly altering test results. To decrease the effect of the rough surface we used gravel and sand as a load distribution layer on top (Figure 3.). First 4/8 mm gravel was used to “wedge” the foamglass particles’ surface and create a more flat face. This is turn was then covered with 0/1 mm sand to create the smooth surface on which the load plate can uniformly transfer loads.

This smoothing of the surface was similar to what was observed during field testing, where the particles were rearranged during compaction and a fragmentation of the particles could be observed, creating a smooth surface.

This method of surface preparation decreased the scatter of results and reduced the deformation of the samples as well (initial deformations could reach up to 20% which did not corroborate with either other test results or available literature).

Aggregate testing was similar to material testing, in that we conducted compression tests, dynamic load tests and bearing capacity testing.

Compression testing was done using the entire 300 mm diameter sample surface and up to 400 kPa stress in 5 steps including two unloading steps at 200 and 400 kPa. Since the sample was prepared in a rigid container the Young’s module obtained (Table 1.) in these test was the traditional oedometric compression module (Eoed). The resulting compression curve (Figure 4.) is inverse to the expected concave shape of the traditional oedomertic test result. This is most likely due to the fact, that foamglass under higher loading exhibited significant creep.

Although this was not unexpected based on literature, the extent of the creep was significant. Approximately 50% of the deformation was immidiate deformation and the additional 50% was creep. The shape of the creep curve was similar to that of a traditional consolidation curve, and we used the limit of 0,01 mm / minute commonly associated with the end of consolidation to limit creep. Reaching the end of the creep time significantly increased with loading, taking as long as 4-6 hours under 400 kPa.

Figure 3. Foamglass aggregate laboratory sample preparation

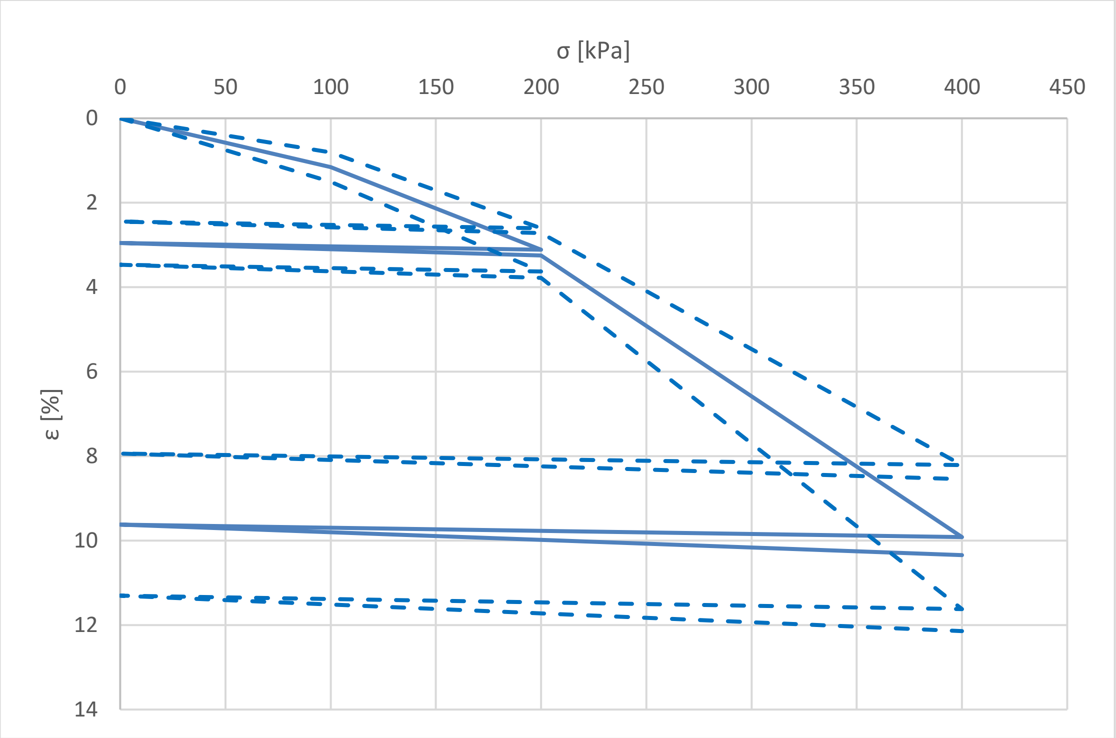

Figure 4. Foamglass aggregate compression test results (soild line is the average test result, the dashed lines represent the scatter of the test series)

Table 1. Foamglass aggregate oedometric test

Load (kPa)	E_{oed} (MPa)	$E_{oed,reloading}$ (MPa)
0-100	8,6	-
100-200	5,1	-
0-200	6,4	67,8
200-400	3,0	-
0-400	4,0	55,4

The compression modules from aggregate testing showed, that despite compacting the samples the compression under the initial loading step was significant, resulting in relatively small compression modules (similar to soft soils, such as silt or silty sand), whereas the reloading module was over an order of magnitude larger. The reloading modules were in similar order of magnitude as that of the material testing results, although it was still only about half of it's value.

Significant differences were observed when comparing the relatice deformation of the samples. While the material sample barely deformed 0,5% under 400 kPa, the aggregate sample had deformations exceeding 10% under similar load. This even though, de material testing was done on an unconfined sample, while aggregate testing was done on a confined sample. Following testing a grain size distribution test was done on the samples to determine and quantify the fragmentation due to the loading. This was later compared to the results of the field testing samples.

Dynamic testing was similar to that of the material sample, with a 1 s load cycle and 1000 cycles at each load stage. The loading schematic was different however, with a 25 – 50 kPa constant load being applied on the sample and an additional 25 – 200 kPa cyclic load.

Bearing capacity testing was done similarly to the material testing setup with the slight difference of the load plate size. It was only about 1/3 of the entire diameter, to be able to apply larger stresses.

3.3 Site testing

While material properties were obtained from laboratory test, the workabilily of foamglass aggregate both in large scale and small scale operations is an equally important question. For this purpose an approximately 200 m2 test site was set up.

The aim of this field tests was to determine what machinery and how effectively can be used to distribute and than compact the aggregate. In order to simulate both large scale construction sites with over 1000 m2 surfaces and smaller, less than 100 m2 construction sites as well, two major surfaces were laid out.

On the first surface, foamglass was laid out in a thick layer and compacter using a heavy roller compactor. The second surface served as the test area for small-scale sites, so a light tandem roller and a heavy and a light plate vibrator was used on a thinner layer of foamglass aggregate.

A load plate test and LWDT tests were carried on each test area and after each layer was laid out and compacted. We compared the results of the different compactions to find the most efficient method and also compared the results with the laboratory tests.

Samples taken after the testing from each test area underwent grain size distribution analysis to determine fragmentation. These results were also compared to the laboratory tests' results.

4 CONCLUSIONS

Introduction of foamglass aggregate to the Hungarian market was met with enthusiasm on both designer and contractor side, but also revealed that there is a lack of experience and technical guidelines regarding its application.

In collaboration with the manufacturers we developed an extensive research programme to define the mechanical parameters of the material and help establish guidance for both designers and contractors.

In the three stage research programme material and aggregate properties along with the workability of the material were analysed.

We were able to corroborate the different test results and form a better understanding of the material behaviour both on a micro and macro scale.

The results from material testing revealed, that the foamglass material itself is rigid (E=100 MPa), but once it is broken down into aggregate form, the stiffness drops to 5-10%. This is probably due to initial compression, as under reloading the stiffness increases tenfold. This sort of behaviour is commonly observed in loosely compacted granular materials.

As the stiffness decreases with loading and foamglass is not expected to take up major loads we suggest, that the aggregate should not be subjected to stresses exceeding 150 kPa. If foamglass is used as a light fill, this corresponds to almost 70 m of fill or a 6 m thick concrete layer. Placed under an industrial floor with a 20 cm thick subgrade layer and 15 cm thick floor slab, assuming a normal load of 50 kPa, total loading is still below 60 kPa.

If the foamglass aggregate is placed on top of the subgrade layer under the floor slab, as XPS blocks would be, the deformation under the floor slab can be expected to be in a similar order of magnitude. Foamglass aggregate would have a compression module of 6-8 MPa, while XPS blocks would be 6-10 MPa depending on the type.

Another similarity to conventional XPS blocks is that both have a long time creep behaviuor of 1,5 – 2,0 %, although long term creep of foamglass aggregate was only extrapolated from a creep curve.

4.1 Future research possibilites

The current research programme determined the properties of geocell both on material level and as an aggregate. During testing we found the limits of the material and our testing equipment as well, which led us to modify the testing procedure as we went along. Now we can use the findings of the entire test programme to further improve future testing, focusing on long-term behaviour and increasing the resolution of the load-settlement graph.

Another important questions is the fragmentation of the material, which was seen both during aggregate and field testing. Although we were able to quantify the fragmentation and correlate it to the loading, it remains to be seen how compaction ratio, grain shape and size influences it. We hope to obtain a better understaing through numerical simulation.

The main research task which remains is the development of guidelines and possible standardization of foamglass aggregate design. This requires a different perspective as foamglass is not just an insulation layer, but it also functions as part of the subgrade layer. As such it must fulfill both heat insulation and load baring layer requirements, which must also be balanced. When installed as part of the subgrade layer, foamglass is able to replace a portion of this layer, but to what extent and under which conditions, remains to be seen.

5 ACKNOWLEDGEMENTS

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