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STRENGTH AND DEFORMABILITY OF MINERAL WOOL SLABS UNDER SHORT – TERM CYCLIC COMPRESSION

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Abstract. The strength and deformability of mineral wools slabs, as well as thermo-insulating characteristics can be attributed to the most important indices determining the popularity of these products in practice. The mechanical resistance and stability of mineral wool slabs in use (at construction) of buildings, as well as the requirements for energy saving and heat conservation are in most cases related to the essential requirements set for a building. The mechanical characteristics of mineral wool slabs are subject to structure, density of material, percentage of binder in product, as well as production techniques. The deformability of mineral wools slabs is determined by mobility of fibrous structure, which is best observed under compression by short-term loads. The article considers the strength and deformability properties of mineral wool products under compression by short-term cyclic load. The results obtained while investigating the compression of mineral wool slabs can be applied for determination of fields and conditions for use of such products in constructions of buildings (floors, ceilings, roofs), as well as for substantiation of respective technical requirements in the normative documents for design of these constructions.

Keywords: mineral wool slabs, short-term compression, deformation, critical stress, cyclic loads.

1. Introduction

In most cases mineral wool boards are used not only as thermal insulating material but also as thermal-structural material. In the construction thermal insulating material is under different short and long-term loading.

Mineral wool products are widely used for thermal insulation of buildings, both at construction of new ones and renovation of old ones (Endriukaitytė *et al.* 2004) .

The advantage of these materials is good heat- and sound-insulating properties. Furthermore, these products are marked by their high resistance to compression. The researches into dependency of compressive resistance and deformability of mineral wool products on components of microstructure (filament mass of mineral wool and percentage of binder) and structure (horizontally layered, vertically layered, corrugated, mixed orientation of filaments) and the mathematical assessment of these factors according to the received experimental data is the most reliable method for designing and production of mineral wool boards with predetermined (required) strength properties Gnip *et al.* (2009).

The strength of thermal-insulating materials under compression should be assessed considering the specifics of deformations development, which manifests itself best in the stress-strain diagram (Vaitkus *et al.* 2006; Gnip *et al.* 2004).

The fibrous thermal insulating materials can be regarded as a mechanical system with chaotically distributed filaments within its volume during formation of the carpet of mineral wool raw materials (with horizontally or vertically oriented, corrugated or mixed structure), non-fibrous insertions and organic or other binder, which interlink separate filaments.

The structure of thermal insulating materials is complicated and the skeleton structure of fiber is difficult to describe mathematically. Therefore, such investigations usually are restricted to assessment of empirical dependencies between certain thermal-physical or physical-mechanical properties.

Subject to production techniques, different fibrous structures of mineral wool products can be received, therefore, separate structural models are to be developed for the structure of each type in attempts to describe the properties of fibrous systems.

The traditional technology of mineral wool allows to obtain the fibrous structure of several types for thermal insulating products. i.e.:

- structure with horizontally oriented fiber;
- structure of spatially oriented fiber (products mostly out of hydro masses);
- structure of vertically oriented fiber;
- structure of corrugated fiber (Архипов 1975; Krivelis, Kaminskas 2000).

Basing on methods of mathematical statistics, the structural model of mineral wool products with horizontally oriented fiber is developed (Широкородюк 2007), and this model is composed of longitudinal and traversal filaments, between which the filaments oriented in the non-horizontal plane are located additionally and these filaments make the elastic elements, which are connected with filaments by rigid bonds.

The structure of spatial orientation of fiber is mostly typical to those products of mineral wool which are molded by a special method out of hydro mass of mineral fibre. In this system the filaments of diameter *d* up to 5–10 μm and length *l* up to 40–50 mm make a spatial skeleton where the sloping filaments occupy the main part of space. They connect with each other, as well as with horizontally and spatially oriented filaments. The joints consist of elastic and rigid punctual bonds. By elastic bonds one can conditionally assess the places of intersection of filaments and friction forces between them and non-fibrous insertions. The rigid punctual bonds simulate the behavior of binder and filaments in the real material. One of particularities of this structure is its even distribution within volume what may explain the high resistance of such products to compression and bending. The compressive resistance grows along with increase in number of filaments with orientation near to vertical (i.e., when angles α and β are approximating to 90°).

The products of vertical fibrous structure stand out by increased compressive strength. In the products made by the conventional conveyor method, about 60–85% of filaments are located horizontally. It is established that only by increasing the percentage of vertical filaments in products up to 50%, their strength grows by 2–3 times without increasing their density. The filaments, which diameter *d* reaches 2–10 μm and length *l* up to 40–50 mm, make a spatial skeleton where filaments of vertical orientation are connected with each other along all height of product. They also connect themselves to filaments of spatial orientation through elastic and rigid punctual bonds. As vertical compressive loads fall practically on vertically oriented filaments, then the strength of these products when compressed along the vertically oriented fibre is higher by 3–7 times than compressed crosswise this fibre.

The idea to produce thermal insulating fibrous products of corrugated structure was based on the universally known effect of increase in rigidity and strength of product upon corrugation (e.g. in case of corrugated cardboard) (Krivelis, Kaminskas 2000; Широкородюк 2007, 2008)

The model of fibrous structure of products of such type consists of vertically oriented filaments with diameter *d* of 2–10 μm and *l* of 40–50 mm, which are connected by elastic and rigid punctual bonds to each other and to filaments of curvilinear and spatial orientation.

The elastic bonds simulate conditionally the places of intersection of these filaments and frictional forces between them and non-fibrous insertions. The punctual bonds connecting filaments and elastic joints simulate the behavior of binder in the real material.

Out of earlier considered models of fibrous structures, the most effective by strength are those with higher percentage of vertical filaments. This is obviously illustrated by the graphical dependencies between the strength in products of different structure when compressed at deformations of 10% and the density of products. However, for production of fibrous structure with higher compressive strength, higher input of energy is required. Especially high energy input is needed with products of anisotropic (spatial) structure out of hydro masses, which have not only high compressive strength, but also lower coefficient of thermal conductivity than products of vertically oriented fiber (Krivelis, Kaminskas 2000; Широкородюк 2007, 2008).

For rational application of mineral wool products for constructive purposes, the data about changes in their deformability under loads are indispensable. With the aim of effective use of mineral wool slabs of increased elasticity for constructive and thermal insulating purposes, it is necessary to investigate their strength and deformability properties under compression by short –term loads. It is of utmost importance to know the kinetics of their deformation indices under compression by loads of various values. In most cases such information is decisive for determination of the most rational applications of slabs of one or other type.

2. Experimental

For investigation the mineral wool boards of partially corrugated and horizontally layered structure with synthetic binder (phenol-formaldehyde resins) were used. The boards were produced in the famous factories of Europe and were meant for thermal insulation of superposed flat roofs, monolithic basement ceilings and floors on overlapping.

In most applications the load of these slabs consisted of leveling concrete blanket, roofing and useful load of floors.

The nominal thickness of used boards was 30, 50, 100, 160 mm and the density from 85 to 195 kg/m^3.

The mineral wool boards were tested after 1–1.5 months from their production. They were conditioned in the environment of temperature of 23±2 ^{o}C and relative moisture of 50±5%. For compressive tests the samples of 200×200 mm were used (LST EN 1602:1998). Their thickness corresponded to the nominal thickness of boards used. These dimensions of samples were selected according to LST EN1602:1998; LST EN826:1998 and LST EN 13162:2009 requirements and suited for the reliable assessment of specific compressive particularities and for measurement of deformability to required precision. The determination of dimensions and density of samples was carried out according to the requirements of LST EN 823:1997; LST EN 1602:1998; LST EN 826:1998 and LST EN 13162:2009 standards.

Four series of samples, 3 samples each, according to LST EN 826 (1998), were prepared out of horizontally layered boards, density of 85 kg/m^3. Four series of samples, 3 samples each, according to LST EN 826 :1998, were prepared out of boards with partially corrugated structure, density of 195 kg/m^3, applicable for thermal insulation of superposed roofs as a top layer. Basing on the requirements LST EN 826:1998, the series of 12 samples of same type, but different thickness of structure were prepared using boards with density of 95–100 kg/m^3, applicable as a bottom layer for thermal insulation of superposed roofs.

The compressive loads, according to LST EN 826:1998 and LST EN 13162:2009, requirements, were perpendicular to surfaces of samples, which coincided to surfaces of boards out of which they were prepared. The board surfaces to be subjected to compression were polished. The standard LST EN 826:1998 and LST EN 13162:2009 sets forth the requirements for geometry of samples, performance of tests, determination of conditional compressive stress $\sigma_{5\ (10\ \%)}$ and initial elasticity modulus E under compression. The tests of compression were performed by computerized testing machine H10KS (Hounsfield, UK). The speed of loading made (0.1 d_s ± 25%) mm/min (here d_s is thickness of sample in millimeters) (LST EN 826:1998; LST EN 13162:2009, the deviation of force meter varied from 1 to 11 N (the extended calibration indeterminacy of force meter being 0.06–0.53%).

In the mineral wool samples, the precision of measurement of longitudinal deformations by shift of machine‘s traverse made 0.01 mm. The tests of compression were performed at relative moisture of air (55±5) % and temperature (23±2) ^{o}C (LST EN 826:1998 and LST EN 13162:2009).

For short-term tests of mineral wool samples, there was used the basic program Qmat Professional Ver.3.83 meant for tests of compression. For each tested sample, the conditional stresses $\sigma_{5\ \%}$ and $\sigma_{10\ \%}$ were calculated, as well as the initial modulus of elasticity E, and the diagram of deformations was drawn.

At procession of these stress-strain diagrams (Fig. 1) (Gnip *et al.* 2009; Vaitkus *et al.* 2006), the critical relative deformations ε_{cr} were determined, below which the quasilinear dependency $\sigma = f(\varepsilon)$ is maintained and above which a considerable growth of deformations and deviation from linear dependency is observed.

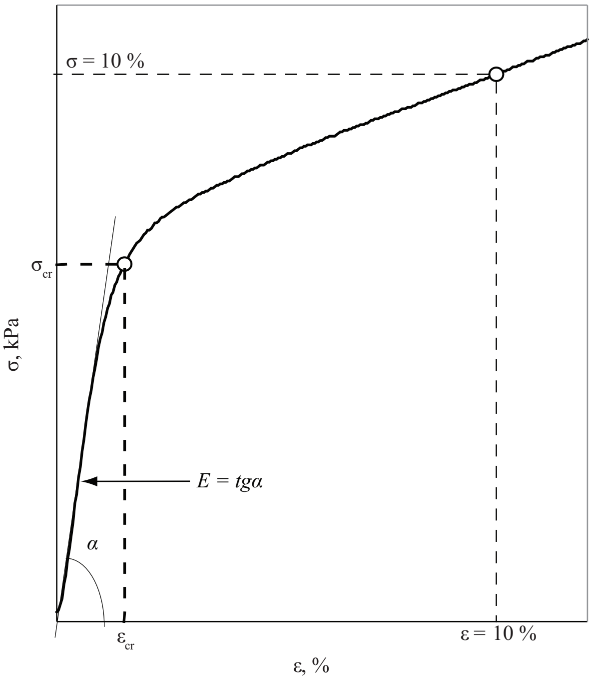

Fig. 1. Scheme of the stress-strain diagram under compressive loading of mineral wool products

The strength index $\sigma_{10\ \%}$ can be used for assessment of impact of various factors, such as density, type and percentage of binder, structure of product, to strength properties of products at the stage of their production and designing. However, when using these products for constructive – heat-insulating purposes, it is necessary to evaluate σ_{cr}, which better characterizes the bearing properties (Gnip *et al.* 2004).

The values of critical stresses σ_{cr} were determined from the stress-strain diagrams drawn during the tests. The methods for determination of critical stress are based on one-valuedness of stress (the ordinate) at the end of the linear length OA in the diagram of compression (at the point A), which characterizes the stress and deformation before passing into the next phase of compression related to appearance of injuries in the mutual contacts between mineral filaments (Gnip *et al.* 2009; Vaitkus *et al.* 2006).

The initial modulus of elasticity under compression E was determined as a tangent of shifting angle in the initial quasilinear length in the stress-strai diagram (Fig. 2).

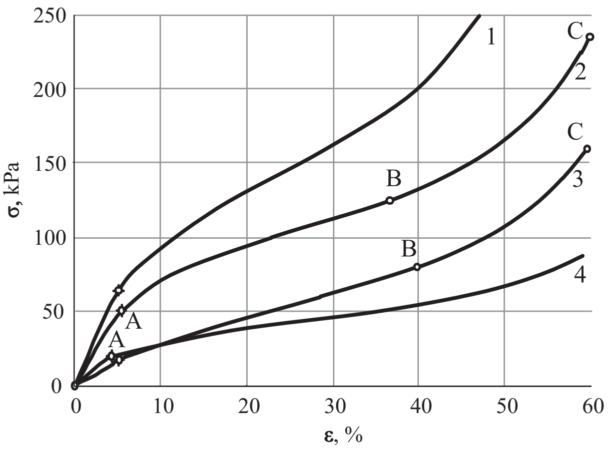

Fig. 2. Changes in relative deformations of mineral wool board samples under compression. Boards of partially corrugated structure, density of 156 kg/m^3: 1 – thickness of 40 mm; 2 – thickness of 70 mm. Boards of horizontally layered structure, density in kg/m^3 (thickness in mm): 3 – 96(80); 4 – 125(30). The ends of percentage zones of total sample squeeze are marked by points

3. Test results

Due to the specific properties of separate raw components and changes in technological parameters of production process, the structure of products and thereby certain indices of deformability can undergo changes (Fig. 1). The deformability of mineral wool boards is determined by mobility of fibrous structure (system) and this mobility manifests itself best of all under short-term compression (Fig. 1, Lines 2 and 3 with Points A, B, C).

The experimental results of compression of mineral wool boards show that, on the whole, the diagram of compression is non-linear. One can see on it characteristic breaks, according to which the diagram can be distributed into 3 zones (Gnip *et al.* 2004a, 2004b, 2007). The initial zone OA characterizes the behaviour of mineral filaments and their contact bonds in the system under load, the shape of which does not change.

This length of graph can be a line or close to line, i.e. one can see the dependency between the deformation close to linear and the load. If the load is increased further (length AB), then along with continuing resistance of the whole system to compression, certain phenomena start exerting an ever greater influence and these phenomena are related to injuries of mutual contacts of mineral filaments. In the initial part of zone the deformations of these contact filaments joints are insignificant, but with growing load, they start dominating in the process of mineral wool deformation development. The filaments loose their stability, approximate and bend. The length BC of diagram characterizes the transit of the injured system to the stage of compaction and stands out by quick increase in stresses. The ratio of compression diagram zones (lengths) depends on thickness, structure, density and binder percentage of mineral wool product.

According to the Figure 2 strain levels for cyclically loading were selected. Figure 3 shows the compressive stress changes of stone wool products under cyclic loading. When samples reaches up to 10% compressive deformation (such compressive stress is determined for the certification of products) after the first load cycle

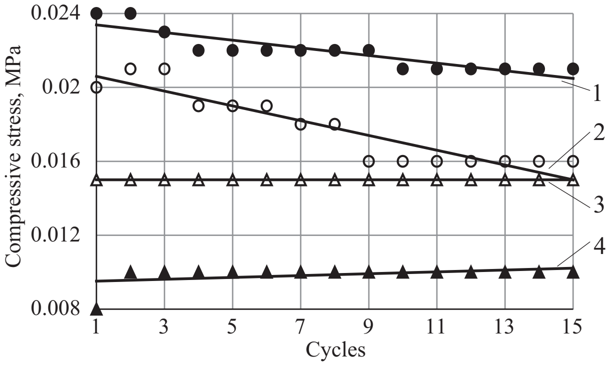

Fig. 3. The dependence of compressive stress on the loading cycles; the sample deformation, %: 1–10, 2–7, 3–5, 4–3; board thickness – 50 mm, ρ = 95 kg/m^3; ●, ○, △, ▲, marked the average value of the test

compressive stress begins to decrease. This indicates that the structure of mineral wool boards irreversible changes. The same view is observed when specimens up to 7% deformation are compressed. Higher heel of second line could be observed due to sample heterogeneity. When the samples to 5% and 3% deformation are loaded decrease or increase of highly compressive stress is not seen. It can be argued that major changes of the structure of mineral wool boards under cyclic loading do not occur.

More visible changes of the structure can be explained in monitoring the modulus of elasticity under compression (Fig. 4). At 10% and 7% of deformation is gradual decrease of modulus of elasticity. At 5% and 3% deformation compressive stress values are very close. At 10% deformation value of modulus of elasticity after 15 cycles of loading is about three times lower than at 5% and 3% deformation, and approximately 2 times lower than at 7% deformation.

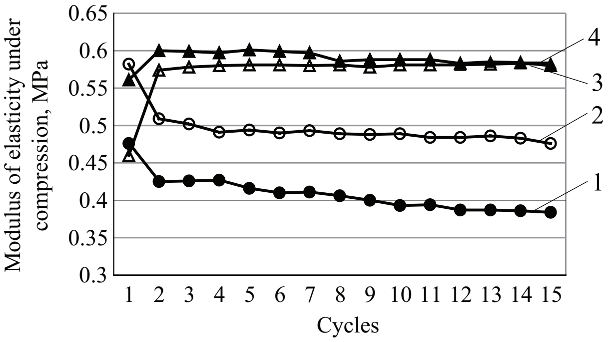

Fig. 4. The dependence of modulus of elasticity under compression on the loading cycles, the sample deformation, %: 1–10, 2–7, 3–5, 4–3; board thickness – 50 mm, ρ = 95 kg/m^3. ●, ○, △, ▲ marked the average value of the test

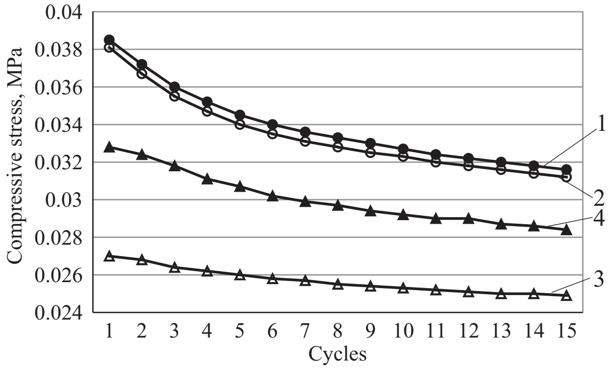

Fig. 5. The dependence of compressive stress on the loading cycles; the sample deformation, %: 1–10, 2–7, 3–5, 4–3; board thickness – 100 mm, ρ = 95 kg/m^3. ●, ○, △, ▲ marked the average value of the test

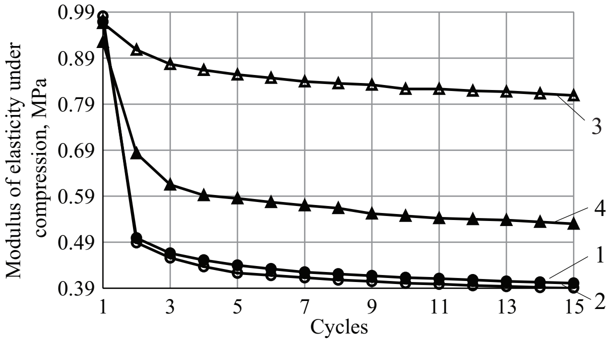

Fig. 6. The dependence of modulus of elasticity under compression of loading cycles, the sample deformation, %: 1–10, 2–7, 3–5, 4–3; board thickness – 100 mm, ρ = 95 kg/m^3. ●, ○, △, ▲ marked the average value of the test

In experiments used stone wool products of 100 mm thickness the character changing of compressive stress are slightly different from that used 50 mm thick product (Fig. 5). At 10% and 7% deformation is significant decrease in compressive stress acting cyclic loads observed. After 15 cycles, compressive stress is not reduced by more than 25%.

At 5% and 3% deformation is also compressive stress reduction observed. After 15 cycles compressive stress decreases almost 16% when the product is deformed by 5% and 8% decrease when the product is deformed by 3%.

Observing the changes of modulus of elasticity (Fig. 6) it can be state that at 10% and 7% deformation the irreversible breakdown of structure occurs in the product after the first load cycle. Modules of elasticity decrease at these deformations after the first cycle by about 50%, while after 15 cycles – about 60%. At 5% deformation are also notable changes in the structure, but more slowly than at 10% and 7% deformation. At 3% deformation is a slow decomposition of structure of stone wool product. Major changes occur in the first two load cycles, the compressive strength decreases by more than 10%, while the remaining 13 cycles – about 7%.

When stone wool boards of 160 mm thickness are used in the sress-load cycles diagram (Fig. 7) at 10%, 7% and 5% deformation similar crushing character of the structure and reduction of the stress is observed. At 3% deformation decreasing of stress intensity is slower and after 15 load cycles is approximately 7%.

Similar changes are monitored by determining the modulus of elasticity under compressive (Fig. 8). At 10% compressive deformation reduction of modulus values after 15 cycles of loading is as many as 77%, at 7% deformation – 67%, at 5% deformation – 52%.

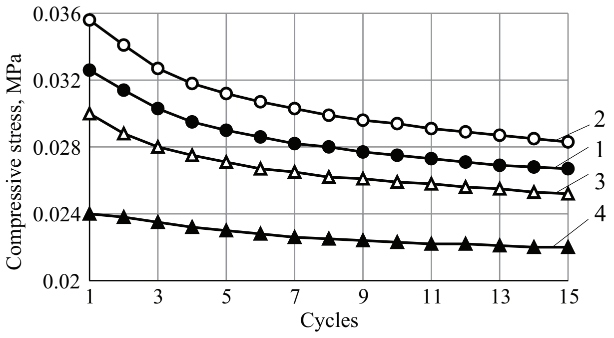

Fig. 7. The dependence of compressive stress on the loading cycles; the sample deformation, %: 1–10, 2–7, 3–5, 4–3; board thickness – 160 mm, ρ = 95 kg/m^3. ●, ○, Δ, ▲ marked the average value of the test

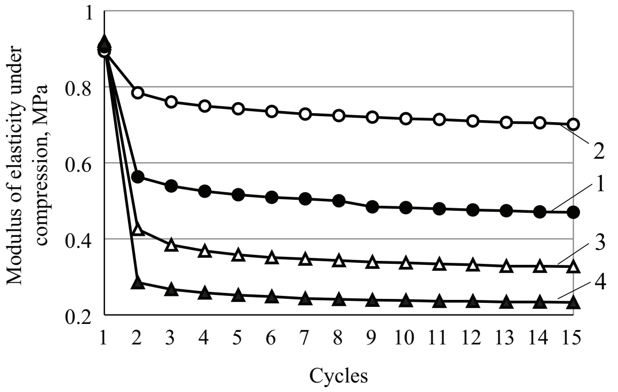

Fig. 8. The dependence of modulus of elasticity under compression of loading cycles, the sample deformation, %: 1–10, 2–7, 3–5, 4–3; board thickness – 160 mm, ρ = 95 kg/m^3. ●, ○, Δ, ▲ marked the average value of the test.

Decrease of maximum values of modulus of elasticity under compression after the first load cycle is observed. At 3% deformation reduction of modulus of elasticity after 15 load cycles is around 25%. 17% decrease of this value after the first load cycle is observed.

Comparing 3, 5 and 7 figures compressive stress decreasing with increasing thickness of mineral wool boards is observed. It can be assumed that deformation in mineral wool products is distributed unevenly. In weaker layers deformation is very high, and in stronger layers the deformation is very small. Due to the large deformation of weaker layers of stone wool is deterioration of the structure and the greater thickness of the product, the more intense degradation of the structure of the mineral wool layers of weaker and more compressive stress wool reduction throughout the product.

Comparing 4, 6 and 8 figures a clear decrease in compression modulus with increasing thickness of stone wool boards is observed. Determining the modulus of elasticity less influence has heterogeneity of samples, while the modulus of elasticity in the initial section of the compression diagram is determined.

4. Conclusions

Changes of the structure in mineral wool boards under compression depends on the product type, thickness and density. This changes shows stress-strain diagram. The diagram can be distributed into 3 zones. Each zone describes different deformation mechanism.

Under cyclic short-term compression deformation mechanism depends on the deformation level.

After cyclic loading compressive stress and modulus of elasticity decrease. The biggest decrease is after first loading. While test specimen are 50 mm thickness and deformation 5% or 3%, decrease intensivity of compressive stress and modulus of elasticity is negligible When deformation is 10% or 7% compressive stress and modulus of elasticity decrease after every loading. The same deformation mechanism shows diagrams when 100 mm and 160 mm thickness specimens are used. In this case at 5% deformation starts intensively decrease of compressive stress and modulus of elasticity. At 3% deformation decrease of compressive stress reaches 25%. 17% decrease of this value after the first load cycle is observed.

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TRUMPALAIKĖMIS CIKLINĖMIS APKROVOMIS GNIUŽDOMŲ AKMENS VATOS GAMINIŲ STIPRUMO IR DEFORMACINĖS SAVYBĖS

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Santrauka. Stiprumo ir deformacines akmens vatos gaminių savybes kartu su šilumos izoliacinėmis savybėmis galima priskirti prie svarbiausių rodiklių, lemiančių šių gaminių populiarumą statybos praktikoje. Akmens vatos gaminių, naudojamų pastatų eksploatacijai (statybai), mechaninis atsparumas ir pastovumas bei energijos taupymo ir šilumos išsaugojimo reikalavimai daugeliu atvejų siejami su esminiais statinio reikalavimais. Mineralinės akmens vatos gaminių mechaninės charakteristikos priklauso nuo medžiagos struktūros, tankio, rišiklio kiekio gaminyje ir nuo gamybos technologijos. Akmens vatos plokščių deformatyvumą lemia pluoštinės struktūros paslankumas, kuris geriausia išryškėja gniuždant trumpalaikėmis apkrovomis. Straipsnyje aptariamas ryšys tarp gaminio storio, tankio, struktūros ir stiprumo bei deformacinių rodiklių, pateikiamos šių priklausomybių diagramos. Straipsnyje nagrinėjamos trumpalaikėmis ciklinėmis apkrovomis gniuždomų akmens vatos gaminių stiprumo ir deformacinės savybės. Gautieji akmens vatos plokščių gniuždymo tyrimo rezultatai gali būti pritaikyti nustatant šių gaminių naudojimo pastatų konstrukcijose (grindyse, perdangose, stoguose) sritis ir sąlygas, taip pat pagrindžiant atitinkamus techninius reikalavimus šių konstrukcijų projektavimo normatyviniuose dokumentuose.

Reikšminiai žodžiai: akmens vatos plokštės, trumpalaikis gniuždymas, deformacija, kritinis įtempis, ciklinės apkrovos.

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