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The Possibility of Using Sewage Sludge Pellets as Thermal Insulation

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ABSTRACT

The storage and disposal of sewage sludge from municipal wastewater treatment plants is becoming an increasing problem on a global scale. The attention of scientists is directed to the search for unique technologies to manage them. Firing sewage sludge in furnaces and producing lightweight aggregates and granules constitutes an innovative method of its disposal. The resulting granules could be a substitute for commonly used materials such as perlite, vermiculite, expanded clay, or LSA, and could be used as a secondary material in the construction industry, including road construction, as various types of ballast, and as an equivalent to aggregate in concretes. However, given that sewage sludge is increasingly used in biogas production, it does not completely decompose in the process and is still a problematic waste for many municipal treatment plants. Therefore, the use of sewage sludge pellets in construction, or any other industry, could revolutionize the market. The purpose of the conducted research was to evaluate the heat-insulating properties of granules produced from sewage sludge from the Municipal Wastewater Treatment Plant "Łyna" in Olsztyn used as a heat-insulating material.

Keywords: pellets, thermal insulation, sewage sludge, thermal insulation materials.

INTRODUCTION

The upward trend in the capacity of wastewater treatment plants noted in recent years, the dynamic development of highly efficient biological wastewater treatment technologies, the modernization and construction of new plants, and the introduction of advanced methods of wastewater treatment, including the use of reagents, especially for phosphorus precipitation, leads to the generation of large amounts of municipal sewage sludge. [1–4] According to the data published by the Central Statistical Office, in 2011, 519,000 tons of dry mass of municipal sewage sludge were generated in Poland, while in 2021 this amount was already 585,000 tons. [5] The intensive increase in the mass of sewage sludge produced and the ban on the possibility of landfilling sludge after January 1, 2016 make the management of municipal sewage sludge a very important environmental, technical and economic problem. The choice of the appropriate method of disposal of sewage sludge is mainly influenced by its physicochemical properties, especially the presence of heavy metals, indicating the desirability of a particular method. [1, 6, 7] The rules for the treatment and final management of this waste are also regulated by relevant legislation. [8,9] Very strict criteria imposed on the possibility of natural use of sewage sludge to reduce the spread of hazardous substances in the environment, as well as biological hazards, have influenced the growing interest in innovative technologies for sewage sludge disposal. Taking into account the presence of heavy metals and toxic substances in sludge [10], which limit its agricultural use, the most appropriate way to dispose of sewage sludge is through thermal methods [11,12], including innovative technologies leading to the recovery of valuable raw materials, processing them to enable their use in various industries, or recovery of heat and energy. [13–15] One method is the pelletization of sewage sludge by firing it in furnaces, after it has been drained.[16, 17] The resulting lightweight aggregates and pellets are environmentally safe and can be used in construction as a replacement for commonly used materials such as perlite, vermiculite, expanded clay, or LSA. It would allow using an all-natural and environmentally safe material, while satisfying the need for sludge management. Literature reports indicate the possibility of using sewage sludge in the production of ceramic materials [18] and energy-efficient lightweight aggregate concrete blocks. [19–21] Suchorab et al. [20] showed that sewage sludge can be used as an additive in the production of lightweight aggregates, which can then be successfully employed in the production of lightweight concrete. Importantly, sewage sludge improves the thermal performance of lightweight aggregate concretes, which in turn can increase the energy performance of buildings erected with their use. At the same time, given the fact that the increasingly common use of sewage sludge in biogas production does not completely decompose in the process and is still a problematic waste for many municipal wastewater treatment plants, the use of sewage sludge pellets in construction or any other industry could significantly solve the problems of sewage sludge management.

MATERIALS AND METHODS

The purpose of the conducted research was to determine the physicochemical (chemical composition, grain size), sorption and heat preservation properties of granules obtained from sewage sludge from the Municipal Wastewater Treatment Plant "Łyna" in Olsztyn.

Course of the sewage sludge pelletization process

The granulate, which was collected for testing, comes from the "Łyna" Municipal Wastewater Treatment Plant in Olsztyn, located at ul. Leśna. The wastewater treatment plant (WWTP) was established in 1983, and underwent a thorough modernization in 2004. This facility collects waste from Olsztyn, as well as nearby towns. It is the WWTP in the Warmia-Mazury Province. The WWTP processes approx. 32 thousand m3 of wastewater per day, and produces 20 thousand tons of sludge. The sludge consists of 75–80% water, and therefore must pass through additional drainage and drying devices to be suitable for the next production steps.

The granulate production technology is carried out in four stages and includes mechanical and thermal processes, as shown in the diagram (Figure 1).

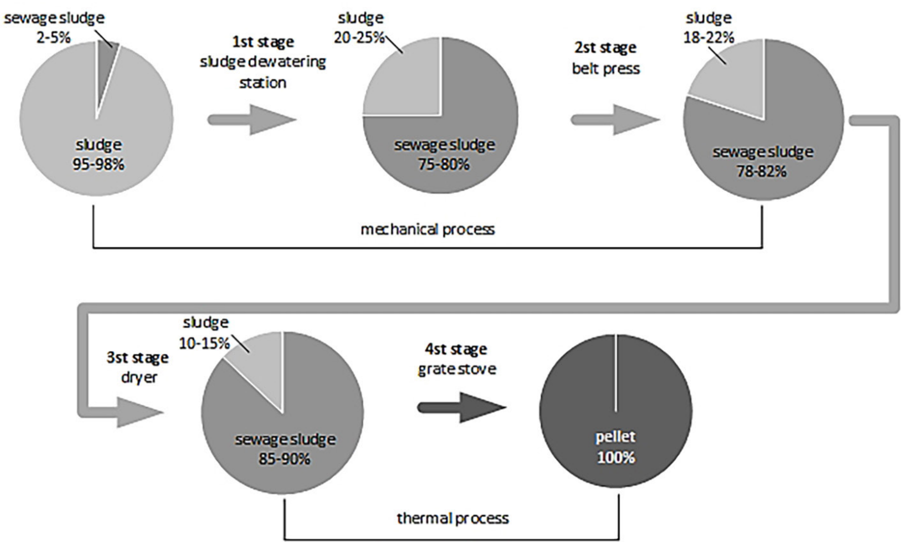

Figure 1. Scheme of the sewage sludge pelletization process

Wastewater flows to the sludge dewatering station, where they are mechanically separated. This is the first step in the entire granules production process. The percentage of sludge in untreated wastewater is 2% to 5% of dry weight. After separation in the dewatering station, about 20–25% of dirty liquid is still present in the sludge. The second stage of production is the introduction of the sludge to the belt press. In order to ensure that pressing proceeds efficiently and effectively, polymers are added to the sludge, which open the pores and allow more wastewater to escape from the inter-clump space. The belt press, squeezing the sediment, leaves from 18 to 22% of wastewater. The above-mentioned stages are included in the first mechanical process, while the second process is the thermal treatment of the sludge. From the belt press, the sludge is fed to the dryer, where the third stage of granulate production begins. The dryer receives sludge with a wastewater content of 18 to 22% of the total weight. If the waste water value is lesser than 18% or greater than 23%, the device will not be able to operate properly. The sludge is dried at 190°C. As a result, a sediment with 85 – 90% dry matter content is obtained. The mass obtained in this way is subjected to pelletization, i.e. rubbing the sludge through a matrix with a diameter of 0.6 cm. It produces thin and short rolls, with length up to 5 cm. Subjecting the sludge to pelletization is necessary to achieve the appropriate parameters during the firing of the pellets.The last stage is transporting the pelletized sludge to the grate furnace. According to environmental regulations, the temperature during firing of the sludge in furnaces should not be lower than 850°C. In case significant amounts of chlorine compounds are present in the sludge, the combustion temperature should be higher than 1100°C. This process is fully monitored by the employees of the treatment plant, hence it is known that the content of chlorine compounds is many times lower than 1%, which enables using temperatures in the grate furnace between 850°C, and 900°C.

The resulting granulate is dry, free from any unpleasant odors and harmful bacteria. The most dangerous elements that make up the sediment can be heavy metals such as cadmium (Cd), lead (Pb), mercury (Hg), or arsenic (As), as well aschromium (Cr), copper (Cu), nickel (Ni) and zinc (Zn). The granulate firing process provides protection against the escape of heavy metals by incorporating them into the crystalline structure of silicates. Apart from them, the granulate does not contain chemical compounds that are foreign to the natural environment, so it can be safely used as a replacement for aggregates in lightweight concrete. [22] The bulk weight of pellets in the loose state is less than 1200 kg/m^3. It is resistant to most natural factors; however, it during mechanical testing it fares poorly, as it crumbles in the fingers.

Determination of physicochemical properties of pellets

In order to determine the content of individual elements in the granulate sample, an EDX-720 X-ray spectrometer was used. It uses liquid nitrogen for examining the elemental composition of the analyzed samples. The sensor in the spectrometer is cooled to a temperature of -190°C, which allows for identifying every element except carbon.

The grain composition of the aggregate was tested on the basis of the PN-EN 933–1:2012 [23] and PN-EN 933–2:1999 [24] standards. In order to determine the grain sizes, standard sieves with following mesh sizes were used: 0.063, 0.125, 0.250, 0.500, 1.0, 2.0, 4.0, 8.0, 16.0 mm. In addition, a RADWAG scale, model PS 4500/C/2, with an accuracy of up to 0.01 grams, as well as a CONTROLS screening shaker were employed. The test was performed using the dry method.

Three samples, each weighing 500 g, were taken to calculate the grain size distribution. According to PN-EN 933–1:2012 with grains having a diameter of $D \leq 4$ mm, the samples with a minimum mass of 0.2 kg were used. Each of the samples was dried at 110°C ± 5°C before final weighing. The shaker was operated for 10 minutes. On the basis of the obtained test results, the grain size curve of pellets was developed.

In accordance with the PN-EN 12667:2002 [25] standard, the thermal conductivity coefficient was tested with the use of a thermal sensor method. A Fox 602 plate apparatus by LaserComp was used for this purpose. The test consisted of passing heat flux through the sample with dimensions of 50 x 50 cm, flowing unidirectionally according to Fourier's law (1), from the heating plate to the cooling plate.

$$q = -\lambda \frac{dT}{dx} \tag{1}$$

where: λ – thermal conductivity coefficient (W/m·K),

q – heat flux flowing through the sample (W/m^2),
dT/dx – temperature gradient over an isothermal flat surface in the sample.

The plate apparatus (Figure 2) is equipped with thermocouples and heat flux converters that record temperature changes between plates ($\Delta T = TC - TZ$), and by the sample thickness (Δx) is determined by pressing it. A standard sample of known thermal conductivity was used to calibrate the plate apparatus.

The granulate was delivered to the laboratory in canvas bags. In order to test it in the Fox 602 plate apparatus, it was placed in a mold with internal dimensions of 500 × 500 mm and a height of 25 mm. The mold was covered with polypropylene (PE) foil. Due to the negligible thickness of the foil, its thermal conductivity coefficient was not included in the calculations. Its task was to prevent the material from becoming damp during possible condensation of water vapor on a cold plate in a plate apparatus [26]. The sample was taken from the bag under laboratory conditions. Then, the granules were poured into a mold and sealed with polypropylene foil. The measurement was performed with the following temperature arrangement: upper heating plate 20°C and lower cooling plate 0°C.

The sorption study consisted of 4 stages:
1. The first stage involved sample preparation. The material is crushed to a grain size of 1–2 mm and the dust parts are removed. Larger diameter grains can be prepared, but the test then takes longer.
2. The second stage involves drying the samples in a laboratory dryer.
3. The third stage consists in introducing the sample into a desiccator, with a salt solution of known relative air humidity placed at its bottom. In order to maintain a constant humidity, the sample is placed over the solution. For this study, salt solutions were used, giving the following relative air humidity: magnesium chloride $MgCl_2$ – 32%, magnesium nitrate $Mg(NO_3)_2$ – 54%, sodium chloride NaCl – 75%, potassium nitrate $K(NO_2)_3$ – 95%.

The fourth step consists in weighing the sample until stabilization of the mass is achieved. The test may take from several weeks to even several months, depending on the material. Sorption is calculated using the formula (2):

$$u_M = \frac{G_1 - G_0}{G_0} \cdot 100, \ [\%] \tag{2}$$

where: u_M – sorption moisture expressed as a percentage of dry matter,
G_0 – mass of the sample when absolutely dry,
G_1 – mass of the sample at sorption equilibrium.

In the sorption study, it is important that the desiccator has a constant relative air humidity. The solution should be stirred from time to time and salt particles, which will dissolve over time, should possibly be added into it [27].

The granulate samples from the municipal wastewater treatment plant were collected in three types: samples with all fractions present in the granulate, samples from the 1.0 mm fraction, samples from the 4.0 mm fraction. After the samples were taken and prepared, they were placed in four desiccators with four different salt solutions to study material sorption under particular humidity conditions. Each of the samples was placed on a mesh installed in a glass desiccator. The vessels were placed in the laboratory so that temperature fluctuations were negligible, i.e. in a shaded place, away from direct sunlight and drafts that could

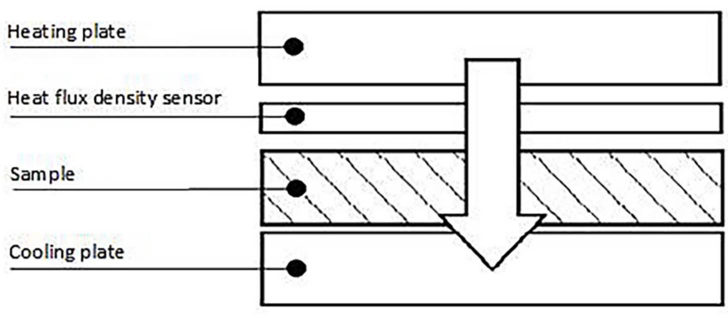

Figure 2. Diagram of a plate apparatus with a heat meter [26]

affect the test results. Observations and measurements were carried out over a month to obtain the most accurate readings possible. The weight gain of the samples was tested each day and the results were recorded in the table. After this time, the samples were removed from the desiccators.

Statistical elaboration of research results

The multidimensional scaling method was used to determine the sorption moisture dependence of the used fractions of the granulate material. The method was first presented by Torgerson in [28] as a method for finding similarity between observations or lack thereof. If the distances between observations are Euclidean distances, the classical MDS gives an easy algebraic solution. In most types of MDS, iterative algorithms are needed because they use many types of data and distances, and it is impossible to find the optimal solution by calculating it from a system of equations. Metric multidimensional scaling is one in which the distances between measurements can be calculated using Euclidean distance [29]. On the other hand, non-metric multidimensional scaling is usually used when there are ordinal-type variables, i.e. those in which it is impossible to calculate the difference between measurements [30].

In this work, although all data is of the quantitative type, it occurs in different units. Therefore, it would be incorrect to use metric multidimensional scaling. The non-metric multidimensional scaling algorithm used in the paper is derived from Kruskal, sometimes called the Kruskal-Shepard algorithm, and was presented in [31]. It relies on minimizing the STRESS (Standardized Residual Sum of Squares) parameter defined as:

$$STRESS = \sqrt{\frac{\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\left(d_{ij}-\delta_{ij}\right)^2}{\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}{d_{ij}}^2}} \qquad (3)$$

where: d_{ij} is the observed distance (or divergence) between observations numbered i and j. On the other hand, the variable δ_{ij} denotes the adjusted distance between the same observations based on monotonic regression [29, 31].

The algorithm is based on a two-step procedure: the first is to achieve a monotonic relationship between the distances between observations (this step is achieved iteratively), while the second is to achieve the lowest possible dimensionality of the transformed data [32]. The iterative procedure involves moving points in a k-dimension ($1 \leq k \leq n - 1$), where n is the number of variables describing the objects) in such a way that the new (transformed in a permissible way) distances between points minimize the STRESS parameter [33]. According to the work [34], values of the STRESS parameter less than 0.15 show a good rescaling of the original data.

The multidimensional scaling method is used to reduce the dimensionality of multidimensional data and visualization to observe differences between groups of observations. Its advantage is that it does not require only quantitative type data. In the past, the method has been used in work on contaminants in the water environment [35,36], the effect of water on the physical properties of concrete [37], but also haptic analysis of physical measurements of roughness and compressibility of materials [38].

The multidimensional scaling and all graphs relating to NMDS were performed using the R package, version 2022.7.0.548 [39] in the RStudio environment [40]. The functions found in the following libraries of this software were used for the present calculations. The tidyverse package includes other libraries, and was created in 2016 by Wickham and the RStudio team [41]. A package of particular importance in this work is ggplot2 [42], which was used to create the graphs. The MASS package was described in [43] and published in the Cran archive in 2009. This library contains functions for non-metric multidimensional scaling, namely the isoMDS function and Shepard. The former was used to reduce the dimensions of the original data. The vegan package was created as a set of methods for analysis primarily for ecologists in 2001 [44], but it includes a stressplot function useful for NMDS, which was used to create a Shepard function plot.

RESULTS AND DISCUSSION

The chemical composition of the pellets is shown in Table 1. The test results of the grain size distribution are presented in the Table 2, and on its basis, the granulation curve of the granulate was created (Figure 3).

As it can be seen, the granules deposited on a sieve with a diameter of 4.0 mm occur in the highest percentage. They account for about 47.0% of the total weight of the granulate. The size of the granules can have a significant effect on the thermal conductivity in later studies.

Table 3 shows the obtained results of the thermal conductivity of the granulate. The graphs (Figure 4) show the changes in sorption moisture over the course of the experiment.

On the basis of the data above, sorption isotherms were also createdin terms of air humidity (Figure 7). In the course of sorption, three characteristic and most important phases can be identified:

- section from 0 to approx. 25–35% with a clear convexity of the curvature to the top of the graph – this is the effect of the presence of water in the form of a mononuclear membrane,
- section from approx. 25–35% to approx. 80–90% with a characteristic convexity of the curvature towards the bottom of the graph – which is caused by the presence of water in the form of a polymolecular membrane,
- the section above 80–90% of air humidity, with a marked increase in the curve upwards indicates the occurrence of capillary condensation, conditioned by the occurrence of concave meniscus on the tested material. [27]

When analyzing the results of the study, it was observed that the samples comprising a fraction of 4.0 mm absorbed more moisture from the air in each of the tested desiccators with salt solutions than the samples comprising a fraction of 1.0 mm and the samples comprising mixed fractions. This proves that there is more water in the form of mononuclear and polymolecular membranes and that there is capillary condensation on the surface of the material granules.

In the case of the samples comprising a fraction of 1.0 mm and the samples comprising mixed fractions, the sorption isotherms are characterized by a common course of the initial phase from 0% to approx. 3.5%. In the remaining two phases, the samples of the mixed fractions show a greater increase in relative humidity in relation to the samples comprising the 1.0 mm fraction.

Considering that, according to European standards, the characteristics of building materials are given for a relative air humidity of 80% and an internal temperature of 23°C, the sorption humidity of polystyrene is close to zero. Sorption humidity

Table 1. Chemical elements contained in the granulate determined with the EDX-720 X-ray spectrometer

Analyte	Fe	Si	Ca	K	Al	Ti	Sr	S	Mn
Contents [%]	38.3	24.8	12,6	9,3	7.0	3.7	1.0	0.8	0.6
Analyte	Zr	Zn	V	Pb	Cu	Rb	Ni	Cr	Y
Contents [%]	0.3	0.3	0.3	0.2	0.2	0.1	0.1	0.1	0.1

Table 2. Determination of the grain composition of granules from sewage sludge

Sewage sludge granulate						
Sieves [mm]	Sample [g]			Arithmetic mean [g]	Content [%]	Through [%]
	First	Second	Third			
16	0.00	0.00	0.00	0.00	0.00	100.00
8	1.10	0.70	3.70	1.83	0.37	99.63
4	209.70	235.20	258.30	234.40	46.88	52.75
2	137.90	131.30	129.80	133.00	26.60	26.15
1	66.80	55.90	56.10	59.60	11.92	14.23
0.5	24.40	20.70	16.30	20.47	4.09	10.14
0.25	18.30	16.40	10.10	14.93	2.99	7.15
0.125	14.70	13.30	8.10	12.03	2.41	4.75
0.063	11.00	11.00	6.60	9.53	1.91	2.84
0	16.10	15.50	11.00	14.20	2.84	0.00
∑	500.00	500.00	500.00	500.00	100.00	-

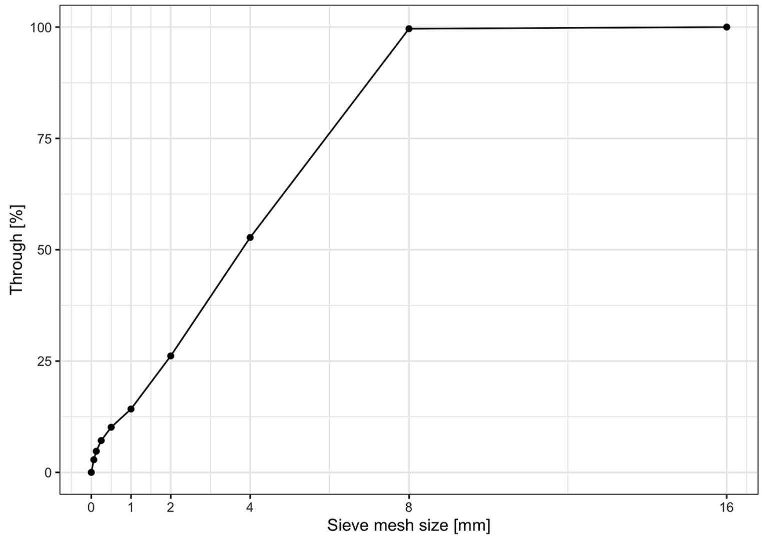

Figure 3. Sludge grain size distribution curve

Table 3. Results of the thermal conductivity test of granulate from sewage sludge T_{Upper} = 20°C, T_{Lower} = 0°C

Parameter	Sample number									
	1	2	3	4	5	6	7	8	9	10
Sample thickness [mm]	26.06	25.81	25.71	25.62	25.63	25.53	25.48	25.46	25.40	25.38
Thermal conductivity [W/mK]	0.09651	0.09660	0.09675	0.09687	0.09729	0.09723	0.09730	0.09748	0.9751	0.09763

of loose mineral wool at 75% humidity does not exceed 0.14%, loose cellulose 12.14%, and hemp fibers 9.89%. [45] Higher humidity than 80% favors the formation of mold and fungi; therefore, it is indicated as the maximum permissible internal humidity of rooms.

The tested material is characterized by a humidity content of 2.80% and air humidity (in the desiccator in which the sorption of the material is tested) of 80% These values are lower than those given for the above-mentioned building materials, such as concrete, silicate or ceramic brick, which proves the satisfactory result of the tests carried out.

Non-metric multidimensional scaling (NMDS) using Kruskal's method was used to visually represent the similarity between measurements of the previously presented parameters in samples from the 1mm, 4mm and mixed fractions. Figure 8 shows the high similarity between the samples

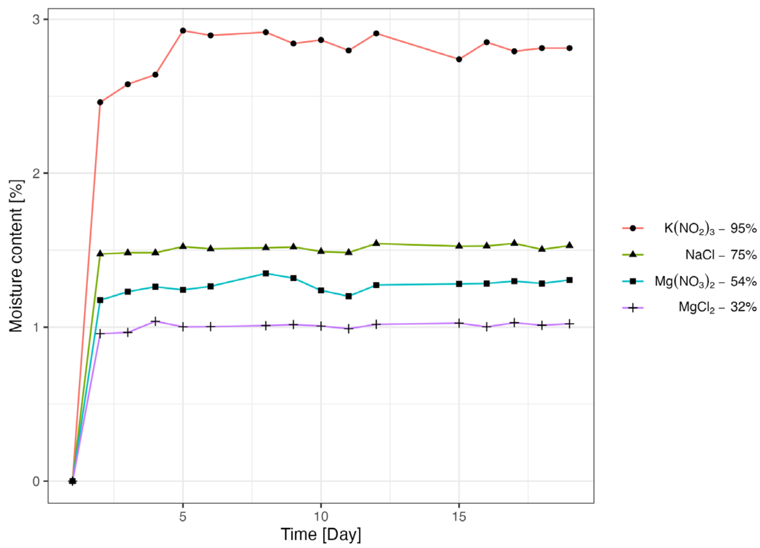

Figure 4. Sorption plot – samples comprising a fraction of 1.0 mm

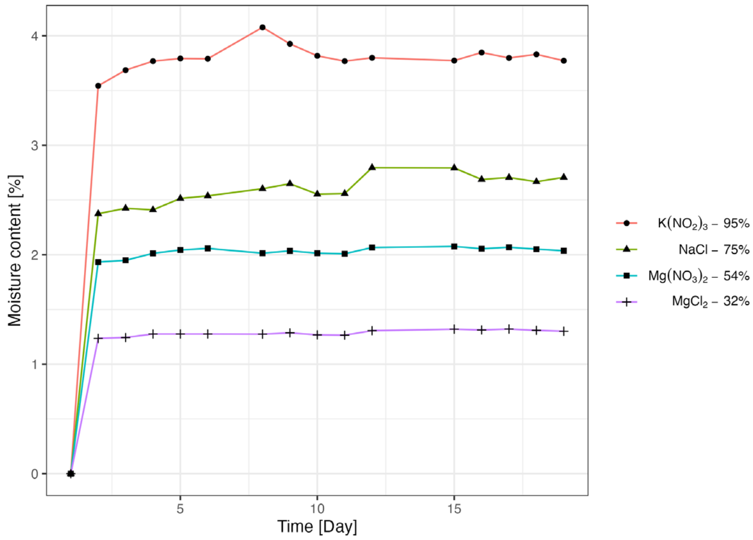

Figure 5. Sorption plot – samples comprising a fraction of 4.0 mm

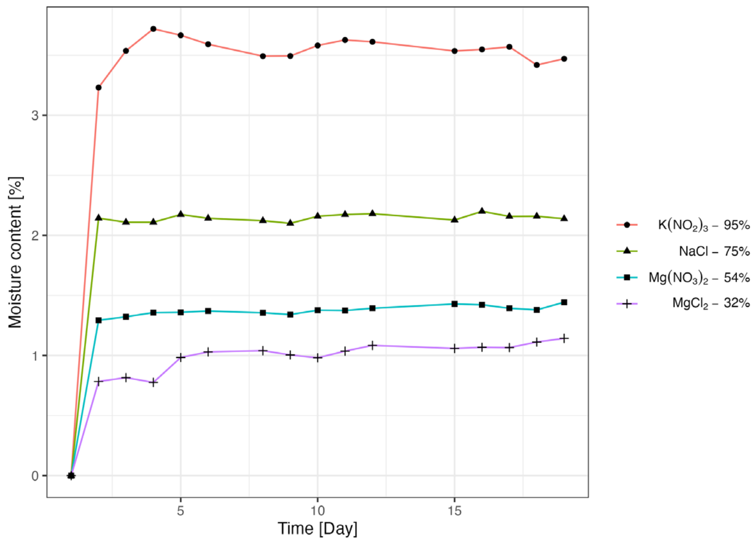

Figure 6. Sorption plot – samples comprising mixed fractions

within each fraction – the observation labels begin with the corresponding symbols, i.e. F1 for the 1mm fraction, F4, for the 4mm fraction, and MF for the mixed fraction. The only points that stand out from the rest, thus being the furthest from the other clusters, are observations F1_1303, F4_1303 and MF_1303. These are the reference observations for each of the studied fractions, which were measured on 13.03.2017. Simultaneously, they form a separate cluster on the left side of the system determined by NMDS.

Figure 9 also confirms the assumption of clustering in the analyzed data. Namely, according to the k-means clustering performed on the rescaled, two-dimensional data for k=4, it turned out that the data were correctly classified into F1, F4 and MF groups except for 3 control observations.

The value of the STRESS function for non-metric dimensional scaling was 0.08. The closer to 0 the value, the better the mapping of the principal components entering the original dataset, so the value can be considered satisfactory. The graph of the Shepard function, shown in Figure 10, does not coincide with the graph of the identity function, but this may be due to the small size of the analyzed dataset (48 observations).

Figure 11 shows a decrease in the STRESS value in the applied non-metric multidimensional scaling algorithm for cases from 2 to 12 dimensions. It can be seen that a significant decrease in this value occurs only at 4 dimensions (STRESS=0.008), but such a representation of the original data space would not allow visualization and organoleptic observation of differences

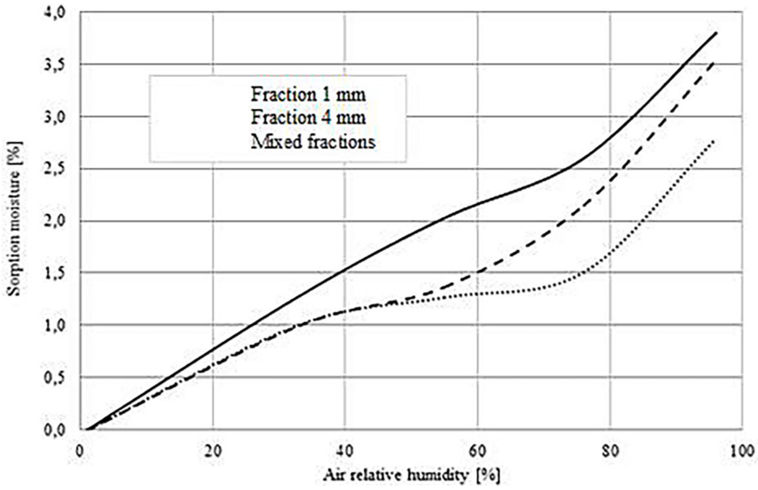

Figure 7. Moisture sorption isotherms from sample air

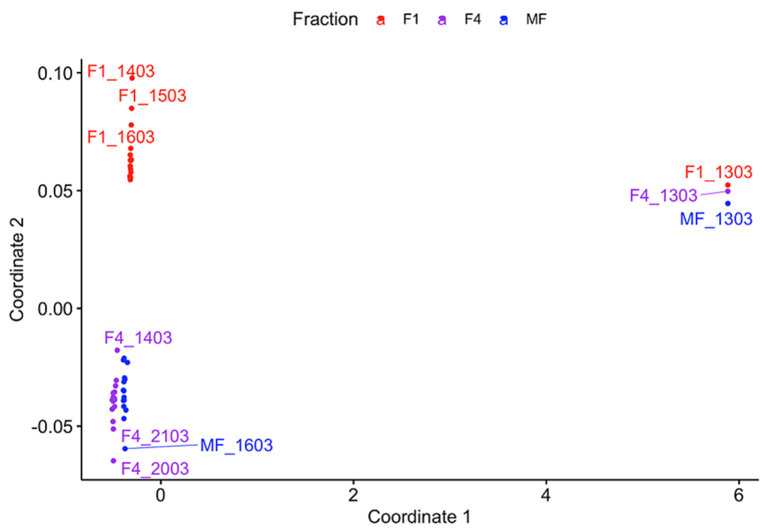

Figure 8. Nonmetric multidimensional scaling results on 2-dimensional plane

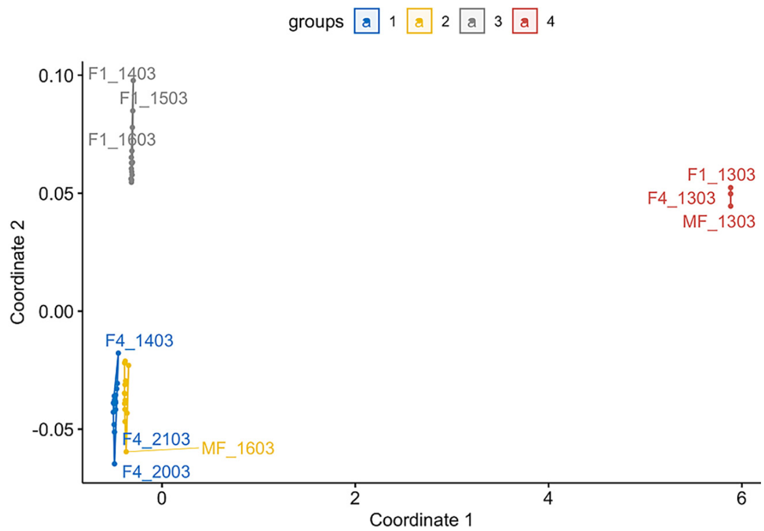

Figure 9. K-means clustering algorithm result on plane derived from NMDS

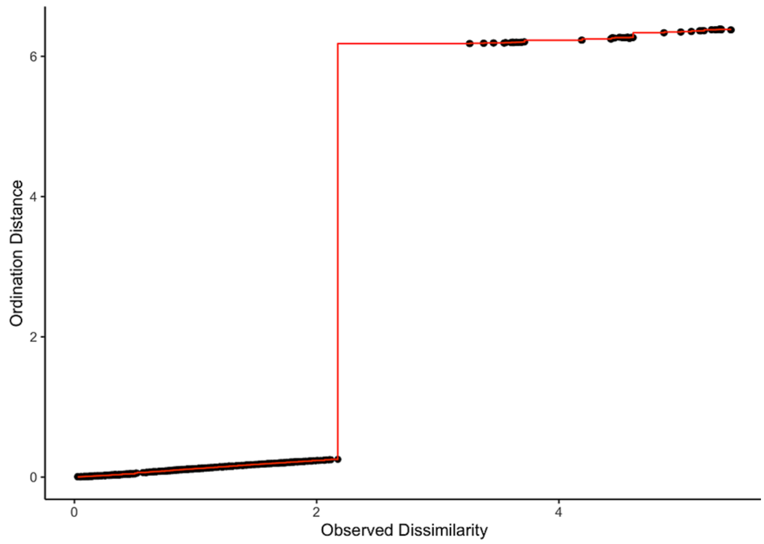

Figure 10. Plot of true and obtained dissimilarity between objects STRESS=0.09

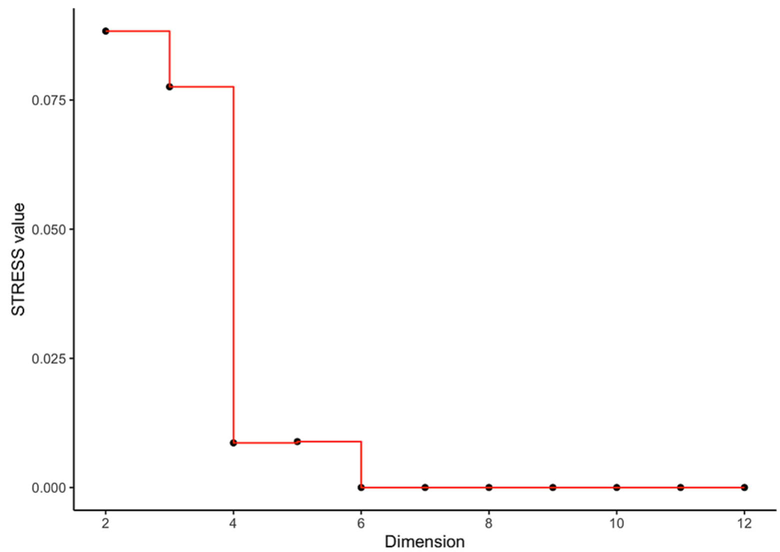

Figure 11. Plot of STRESS values with different number of NMDS dimensions

between observations. STRESS values for the number of dimensions greater than or equal to 6 are approximately equal to 0. Increasing the dimensionality of the space from 2 to 3 dimensions does not significantly reduce STRESS values.

CONCLUSIONS

The conducted tests of the thermal conductivity coefficient showed that the granulate from the sewage sludge is not the best thermal insulation material. Nevertheless, it meets the requirements for insulating materials used in engineering structures and has a thermal conductivity λ of less than 0.175 W/m×K.

Contrary to the results of heat conduction tests, the granulate showed low sorption of moisture from the air, which is a desirable phenomenon among the materials used as thermal insulation. At relative air humidity equal to 80%, the material absorbed less water than commonly used concrete, silicate or ceramic bricks. It can be seen that the sorption moisture depends on the used material fractions. Lower moisture content was measured for the fine fraction. The obtained results may be useful for engineers planning to optimize the granulometry of prospective loose backfill insulation utilizing pellets from wastewater treatment plants.

The conducted research showed that the granules from sewage sludge could be used in lightweight concretes as a replacement for the aggregates commonly used in construction. However, further studies of the chemical interaction between the granulate and the components of the concrete and the reinforcing steel should be carried out.

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