

# CHEMICAL TECHNOLOGIES, MATERIALS SCIENCES, METALLURGY ХИМИЧЕСКИЕ ТЕХНОЛОГИИ, НАУКИ О МАТЕРИАЛАХ, МЕТАЛЛУРГИЯ



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## The Use of Straw, Coal and Foam to Improve Thermal and Mechanical Properties of Polyurethane

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### Abstract

**Introduction.** Polyurethane, a material composed of polyol and isocyanate, has been recognized as one of the most efficient thermal insulation materials. However, its insulating properties can be further enhanced by incorporating additives such as straw, coal, or foam. Nevertheless, there is a concern regarding the potential for reduced adhesion. The literature describes the introduction of additives into polyurethane as strengthening components. The limited volumes of fillers are justified by the need to maintain the uniformity of the samples. It should be noted that most additives did not significantly impact the thermal properties of the material. The aim of this research is to investigate the possibility of improving thermal and mechanical characteristics of polyurethane by adding fillers.

**Materials and Methods.** Samples of polyurethane from the company "Daumerk" (Turkey), with various additives, were experimentally studied. In the first stage, four samples were prepared without fillers, and in the second stage, six more samples were created with 5% and 10% additions of coal, straw, and foam. Thermal conductivity was assessed using a hot plate method, while compression testing was conducted using a device that could apply loads up to 5,000 N. Acoustic properties were measured with an instrument that evaluated the sound absorption coefficient.

**Results.** The sample containing 63% isocyanate and 37% polyol had the lowest density of 33 kg/m<sup>3</sup>. This was due to the absence of fillers and the homogeneous structure of the material. Adding 5% fillers did not significantly affect the density of the sample because the densities of straw and foam were close to the density of polyurethane without additives. Low water absorption was found in samples without additives (50% isocyanate and 50% polyol) and with 5% addition of foam (62% isocyanate and 33% polyol). As the proportion of isocyanate increased, water absorption increased. Samples with higher density and no fillers had better sound absorption. With a low additive content (5%), sound absorption increased due to the homogeneity of the structure. However, with a higher additive volume (10%), sound absorption decreased due to weaker bonds in the material. Adding 10% foam provided maximum resistance to water.

**Discussion and Conclusion.** The optimal filler content improves thermal, mechanical, and acoustic properties of polyurethane, opening up new possibilities for its application. However, a large volume of fillers can have a negative effect on the material's properties. For example, a high straw content can significantly increase water absorption. Therefore, it is recommended to use 5% straw content in combination with 62% isocyanate and 33% polyol, resulting in a thermal conductivity of 0.023 W/m·K, a density of 37 kg/m<sup>3</sup>, and a compressive strength of 358 kN/m<sup>2</sup>. These results confirm the feasibility and possibility of using fillers, such as coal and straw, in the production of polyurethane materials. A modified composition with these fillers would be cheaper and possess better physical properties than the original material. Further research could focus on studying other types of fillers for polyurethane.

**Keywords:** thermal insulation properties of polyurethane, polyurethane with the addition of coal, polyurethane with the addition of straw

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Оригинальное эмпирическое исследование

## Использование соломы, угля и пенопласта для улучшения термических и механических характеристик полиуретана

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### Аннотация

**Введение.** Полиуретан, состоящий из полиола и изоцианата, считается одним из самых эффективных теплоизоляционных материалов. Вероятно, его изоляционные качества можно усилить, если добавить такие наполнители, как солома, уголь и пенопласт. При этом есть риск ухудшения сцепления. В литературе описано введение добавок в полиуретан как укрепляющих компонентов. Незначительные объемы наполнителей объясняются необходимостью сохранить однородность образцов. Отметим, что большинство добавок не оказали значительного влияния на термические свойства. Цель данного исследования — изучить возможность повышения термических и механических характеристик полиуретана добавлением наполнителей.

**Материалы и методы.** Изучались образцы полиуретана компании «Даумерк» (Daumerk, Турция) с различными добавками: четыре образца без наполнителей и шесть с добавлением 5 % и 10 % угля, соломы и пенопласта. Теплопроводность оценивали методом горячей пластины. Для испытания на сжатие задействовали устройство, обеспечивающее нагрузку до 5 000 Н. Акустические свойства измеряли прибором для оценки звукопоглощения.

**Результаты исследования.** Образец, содержащий 63 % изоцианата и 37 % полиола, обладает наименьшей плотностью (33 кг/м<sup>3</sup>). Причины: отсутствие наполнителей и однородная структура материала. Добавление 5 % наполнителей не оказало значительного влияния на плотность образца, потому что плотности соломы и пенопласта близки к плотности полиуретана без добавок. Низкое водопоглощение — у образцов без добавок (50 % изоцианата и 50 % полиола) и с добавкой пенопласта 5% (62 % изоцианата и 33 % полиола). При увеличении доли изоцианата водопоглощение растет. Образцы с более высокой плотностью и без наполнителей демонстрируют лучшие показатели звукопоглощения. При низком содержании добавок (5 %) звукопоглощение увеличивается благодаря однородности структуры. При более высоком объеме добавок (10 %) звукопоглощение снижается из-за недостаточно прочных связей в материале. Добавка 10 % пенопласта обеспечивает максимальную устойчивость к воде.

**Обсуждение и заключение.** Оптимальное содержание наполнителей улучшает термические, механические и акустические характеристики полиуретана, открывая новые возможности для его применения. Большой объем наполнителей негативно сказывается на свойствах материала. Так, высокое содержание соломы заметно повышает водопоглощение. Рекомендуется использовать 5 % соломы с 62 % изоцианата и 33 % полиола. Теплопроводность этого состава — 0,023 Вт/м·К, плотность — 37 кг/м<sup>3</sup>, прочность на сжатие — 358 кН/м<sup>2</sup>. Результаты исследования подтверждают возможность и целесообразность использования наполнителей (особенно угля и соломы) в производстве полиуретановых материалов. Модифицированный состав будет дешевле и с лучшими физическими характеристиками. Задачей дальнейших исследований может быть изучение других видов наполнителей для полиуретана.

**Ключевые слова:** теплоизоляционные свойства полиуретана, полиуретан с добавлением угля, полиуретан с добавлением соломы

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**Introduction.** The global energy agenda has led to active research on thermal insulation materials. The effectiveness of these materials is studied in relation to their characteristics and composition [1]. Polyurethane, hardened foam made of polyol and isocyanate, is considered one of the best insulating materials [2]. Natural fillers can be added to the composition to improve its performance, but only in small amounts, as excessive use can lead to decreased adhesion [3].

The scientific literature provides evidence that the addition of straw and coal can improve thermal, mechanical and acoustic properties of polyurethane [4].

The authors [5] obtained a set of samples by mixing purified soil heated to a temperature of 105°C with polyurethane components. Some samples were shaped, others were taken after free foaming. Compression, flexibility, fluidity, and freezing tests were performed. The results were compared with experimental data on marble, ceramic, and basalt samples. It was found that the mixture with purified soil has the best impact strength. However, it is necessary to take into account the lower specific gravity of polyurethane samples.

The researchers [6] integrated recycled and pure polyurethane in various ratios (maximum — 10%). The samples with increased amount of recycled polyurethane foamed faster and had better tensile and compressive characteristics.

In [7], walnut and hazelnut shells are considered as filler for polyurethane. It has been proven that these additives combine well with polyurethane components. Even their small amount increases the mechanical properties and thermal stability of samples.

The possibility of using silica gel as a reinforcing additive for polyurethane was shown in [8]. Four samples containing 0%, 1%, 3% and 5% silica gel were studied. The tests showed that at 5%, thermal conductivity decreased to 0.0268 (W/m·K) compared to a material without a filler of 0.0314 (W/m·K). Stress and compressive strengths increased by 18% with the addition of 3% silica gel, but decreased if the filler volume exceeded 3%.

The author [9] added grain hulls and rubber from recycled tires to polyurethane. The optimal proportion of additives has been established: 5% of grain hulls and 15% of rubber. This ratio ensures the maximum mechanical strength of the material.

The aim of the scientific research described in this article is to study the possibility of improving the properties of polyurethane using additives: straw, coal and foam. It is assumed that the proposed solution will reduce thermal conductivity while maintaining good mechanical, acoustic and physical characteristics. In this case, it will be possible to talk about the economic feasibility of using modified material to increase the energy efficiency of facilities. Moreover, the composition itself should be more affordable, since polyurethane components are partially replaced by cheap fillers.

**Materials and Methods.** During thermal, physical, mechanical, and acoustic testing, samples of Daumerk polyurethane (Turkey) with and without additives were examined.

**Sample preparation.** At the first stage of the experiments, four samples of polyurethane were prepared. The main ingredients were mixed without any fillers and then poured into a mold (Fig. 1).



Fig. 1. Wooden sample mold

The dimensions of the wooden mold: 150×150×10 mm. Transparent glue was applied to the bottom and inner surface of the lid to prevent the mixture from sticking to the mold. After pouring the mixture, the lid was attached with four screws.

Table 1 shows samples with different ratios of polyurethane components.

Table 1

Polyurethane Components in the Samples, %

| Component  | Sample No. |    |    |    |
|------------|------------|----|----|----|
|            | 1          | 2  | 3  | 4  |
| Isocyanate | 50         | 60 | 63 | 65 |
| Polyol     | 50         | 40 | 37 | 35 |

At the second stage, the optimal ratios of isocyanate and polyol were selected and six new samples were made. 5% and 10% of coke coal, straw and foam were added to them (Table 2).

Table 2

Composition of Samples with Fillers, %

| Sample No. | 5        | 6         | 7         | 8          | 9        | 10        |
|------------|----------|-----------|-----------|------------|----------|-----------|
| Isocyanate | 62       | 60        | 62        | 60         | 62       | 60        |
| Polyol     | 33       | 30        | 33        | 30         | 33       | 30        |
| Additive   | Foam — 5 | Foam — 10 | Straw — 5 | Straw — 10 | Coal — 5 | Coal — 10 |

**Thermal Testing.** We used an HTC device (Highlight Tech Corp, China), which allowed us to determine thermal conductivity using the hot plate method in accordance with the American standard ASTM C177<sup>1</sup> (Fig. 2).



Fig. 2. Device for determining the coefficient of thermal conductivity

The device took into account the current and the applied voltage, and therefore measured heat flux  $Q$  between different sides of the sample, as well as temperature difference  $\Delta T$  between its upper and lower surfaces. Knowing the dimensions of the sample (area  $A$  and thickness  $l$ ), it was possible to determine coefficient of thermal conductivity  $\lambda$ :

$$Q = A \cdot \lambda \cdot \frac{\Delta T}{l} \rightarrow \lambda = Q \cdot \frac{1}{A \cdot \Delta T}. \quad (1)$$

To ensure accuracy of the results, the device was pre-calibrated using three reference samples made of polystyrene, polyethylene and foam with known thermal conductivity [10]. After that, a calibration graph was constructed (Fig. 3).

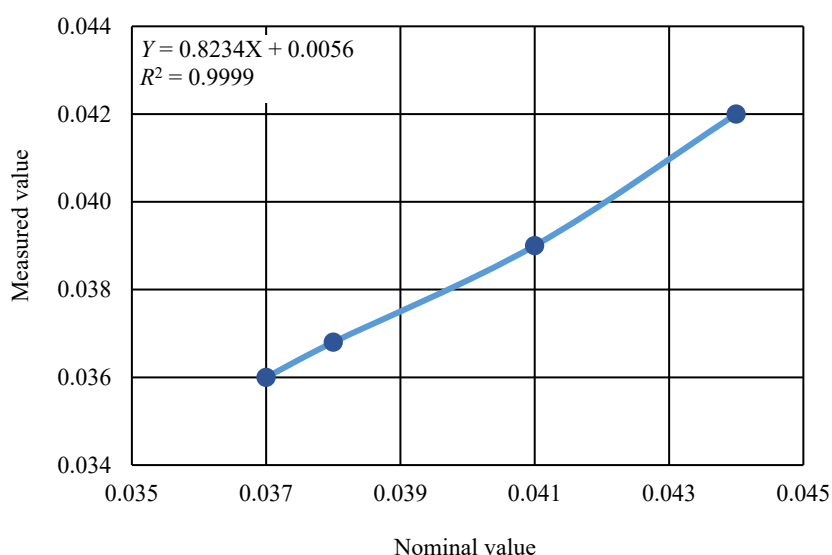


Fig. 3. Calibration graph of the device for measuring thermal conductivity:  
 $R^2$  — coefficient of determination;  $Y$  — variable value

The total error in measuring the coefficient was 5–7%.

<sup>1</sup> ASTM C177–19. Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus. URL: <https://www.astm.org/c0177-19.html> (accessed: 05.12.2024).

**Compression Test.** The compression test was performed in accordance with ISO 844<sup>2</sup>. A device was used (Fig. 4), which allowed applying a compression load of up to 5,000 N to the surface of the sample at a given speed. A load at a rate of 1 mm/min was applied to the samples with sides of 10×10 mm until deformation appeared. The results were recorded by a computer connected to the device with special software.



Fig. 4. Compressive strength testing device

**Density Determination.** To determine the samples density in accordance with ASTM C1622<sup>3</sup> standard, the weight and volume ratios were calculated. To do this, we used:

- scales with an accuracy of  $\pm 0.001$  g (Fig. 5 a),
- vernier calipers with an accuracy of  $\pm 0.01$  mm (Fig. 5 b).



a)



b)

Fig. 5. Devices for determining density:

a — scales; b — vernier calipers

<sup>2</sup> ISO 844:2021. *Standard Practice for Verification of Testing Frame and Specimen Alignment under Compressive Axial Force Application*. URL: <https://cdn.standards.iteh.ai/samples/73560/24ff667df32b4981b29aa870b385bba2/ISO-844-2021.pdf> (accessed: 05.12.2024).

<sup>3</sup> ASTM-C1622:2005-Standard. *Test Method for Apparent Density of Rigid Cellure Plastics*. URL: <https://pdfstandards.shop/product/publishers/astm/astm-c1622-4/> (accessed: 05.12.2024).



Thus, the volume was calculated with an accuracy of  $\pm 0.01 \text{ mm}^3$ , and then the sample density was determined using the formula:

$$\rho = \frac{m}{v}, \quad (2)$$

where  $m$  — mass of the sample, kg;  $v$  — volume of the sample, mm.

**Water Absorption Determination.** To determine water absorption of the samples, they were immersed in water for a certain period of time. It was done in accordance with ASTM D2842<sup>4</sup> standard. The percentage of water absorption was calculated by taking the difference in weight between the sample before and after being immersed, and dividing it by the initial weight of the sample.

**Sound Absorption Determination.** To measure the sound absorption coefficient, a device was used that operated on the “transmitter — receiver” principle in accordance with ISO 10534-1<sup>5</sup> (Fig. 6).

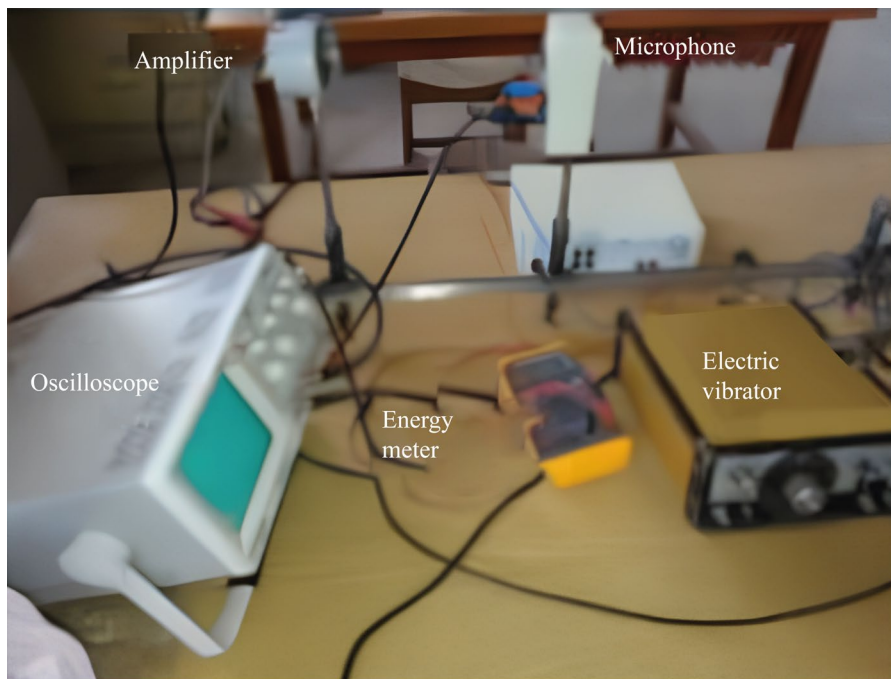


Fig. 6. A device for measuring the sound absorption coefficient

The sample was placed between a sound transmitter and a receiver, and a sound wave with certain energy was sent. The wave's energy was then measured, the frequency range was scanned and analyzed, and the sound absorption coefficient was determined.

Equipment set:

- dual electronic oscilloscope;
- vibrator with a frequency range (1–10 kHz);
- carbon amplifier for transmitting sound waves;
- microphone for receiving sound waves;
- metal bases for mounting the amplifier and microphone;
- bridge on which the amplifier and microphone slide;
- energy meter.

Knowing the wave energy before and after sample installation, it was possible to calculate the sound absorption coefficient:

$$\alpha = \frac{E}{E_0}, \quad (3)$$

where  $\alpha$  — sound absorption coefficient;  $E$  — wave energy after sample installation (volts);  $E_0$  — wave energy before sample installation (volts).

<sup>4</sup> ASTM D2842–19. *Standard Test Method for Water Absorption of Rigid Cellular Plastics*. URL: <https://www.astm.org/d2842-19.html> (accessed: 05.12.2024).

<sup>5</sup> ISO 10534-1:1996. *Acoustics — Determination of sound absorption coefficient and impedance in impedance tubes*. URL: <https://cdn.standards.itch.ai/samples/18603/3bfc0004b5024b2f9d8e3f19879aaf61/ISO-10534-1-1996.pdf> (accessed: 05.12.2024).

## Results

**Density.** Figure 7 shows the results of determining the density of the tested samples.

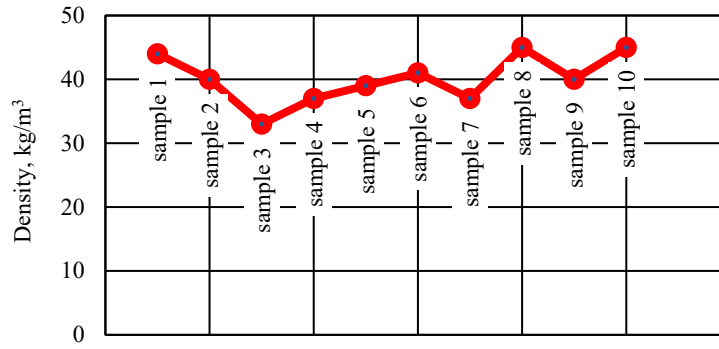


Fig. 7. Comparison of samples by density

The lowest density of sample 3 (33 kg/m³) was explained by the absence of fillers and the uniformity of its structure. The addition of fillers, especially in a volume of 5%, did not significantly affect the density. This was due, firstly, to the insignificant proportion of the additive. Secondly, the density of additives (especially straw and foam) was close to the density of polyurethane without additives.

**Water Absorption.** The results of water absorption tests are shown in Figure 8.

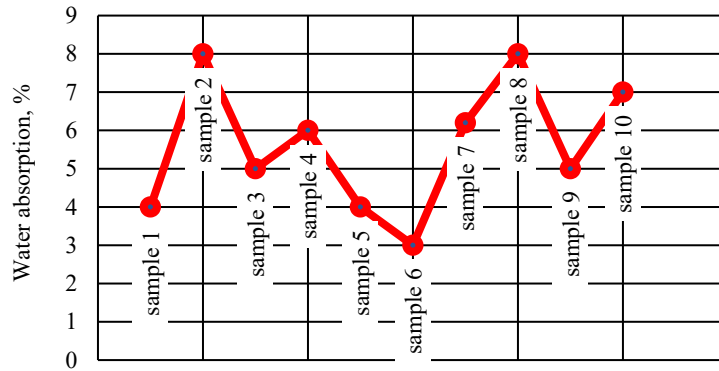


Fig. 8. Comparison of samples by water absorption

A low level of water absorption was recorded in samples without additives (50% isocyanate and 50% polyol) and with the addition of 5% foam (62% isocyanate and 33% polyol). With an increase in the proportion of isocyanate, the water absorption level increased, especially in samples 8 and 10 with 10% straw and coal. This was consistent with the results obtained by other researchers [11]. Sample 2 deviated from the general rule, which may be related to the specifics of its preparation. It is known that straw actively absorbs water. Accordingly, the water absorption is higher for samples with straw. When foam granules were added, on the contrary, water absorption decreased due to the high resistance of this material to water. For this reason, the minimum water absorption was observed for sample 6.

**Thermal Properties.** Figure 9 provides the results of thermal tests of the samples.

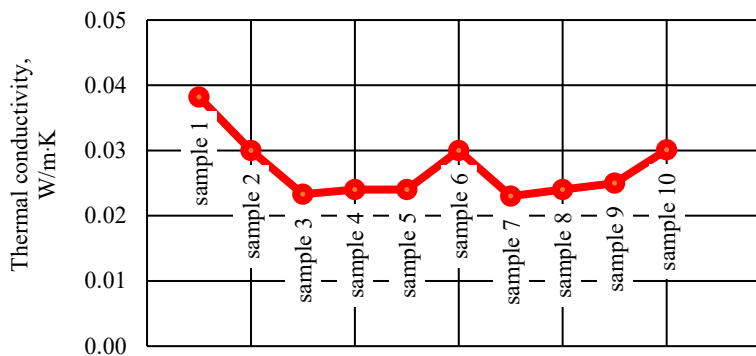


Fig. 9. Comparison of samples by thermal conductivity

The coefficient of thermal conductivity of samples without additives increased with an increase in the proportion of polyol. With high polyol content, the contact between the components improved, the cell sizes decreased, and the

density increased. Dense materials provided more efficient heat transfer, i.e. they had higher thermal conductivity [12]. The addition of foam and coal in high concentrations also increased density and significantly increased thermal conductivity [13]. Adding fillers in small quantities, on the contrary, could improve thermal conductivity. For example, when adding foam and straw in the amount of 5%, it was possible to reduce the values of thermal conductivity to 0.023 W/m·K. The author of [14] obtained almost the same result of 0.024 W/m·K.

**Compressive Strength.** Figure 10 shows the results of determining the compressive strength.

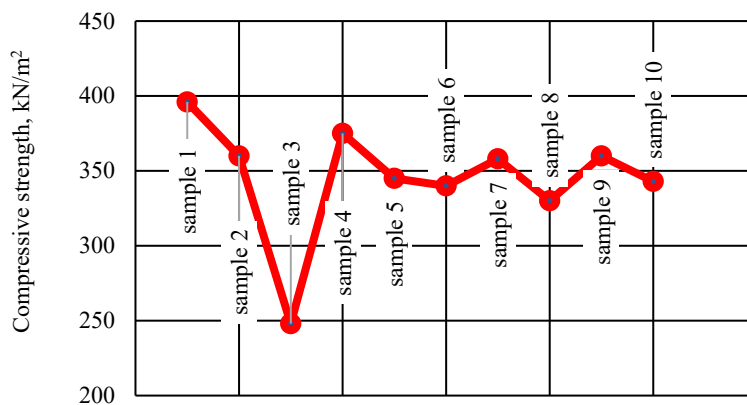


Fig. 10. Comparison of samples by compressive strength

Compressive strength was proportional to density of the material; therefore, in samples without additives, it increased with increasing polyol content. With the addition of 5% straw and coal, the compressive strength was high due to the uniformity of the cellular structure. With the addition of 10% filler, the mechanical strength decreased due to a decrease in the internal binding force of the sample.

**Acoustic Characteristics.** Figure 11 shows the results of sound absorption tests.

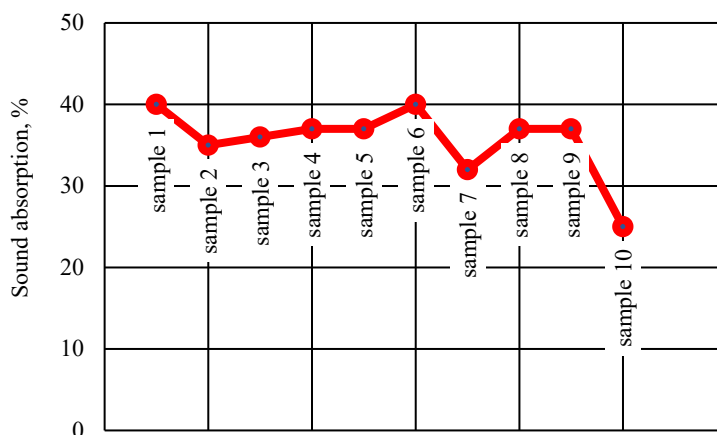


Fig. 11. Comparison of samples by sound absorption

Among the samples without fillers, the densest one had the best score — 1. With a low additive content (5%), sound absorption increased due to the homogeneous cellular structure. With a higher level of additives (10%), it decreased due to insufficiently strong bonds in the sample material.

**Discussion and Conclusion.** The results of the research allow us to draw the following conclusions.

1. The addition of fillers in a certain amount can improve thermal, mechanical and acoustic properties of polyurethane.
2. An increase in the proportion of additives generally worsens the studied properties and may increase water absorption. This happens when adding straw.
3. To achieve optimal results, it is recommended to add 5% straw to polyurethane, consisting of 62% isocyanate and 33% polyol. Thermal conductivity of this sample (number 7) was 0.023 W/m·K with a density of 37 kg/m³ and a compressive strength of 358 kN/m².
4. The values of thermal conductivity and mechanical strength of sample 7 are better by 2% and 4%, respectively, compared with the sample without additives (number 3).
5. The advantages of sample 7 should also include its lower cost. Straw is cheaper than the main components of polyurethane.

In the future, it is planned to study other fillers in terms of their effect on the properties of polyurethane.



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