Advanced Engineering Research (Rostov-on-Don). 2026;26(1):2199. eISSN 2687−1653

UDC 673.7
https://doi.org/10.23947/2687-1653-2026-26-1-2199

Original Empirical Research

Creating Insulation Materials from Unsaturated Polyester and Recycled Tire Rubber

Imad R. Antypas ✉, **Tatyana P. Savostina**
Don State Technical University, Rostov-on-Don, Russian Federation
✉ Imad.antypas@mail.ru

EDN: RAQDMY

Abstract

Introduction. The disposal of automotive tires typically involves landfilling, stockpiling, or incineration. As a result, this causes soil and atmospheric pollution. Scientists have long and actively discussed the recycling of tire rubber as one of the approaches to solving environmental problems. It is known that the use of rubber crumb in composites can reduce their weight and thermal conductivity. However, materials based on unsaturated polyester containing rubber waste have been insufficiently studied. There are contradictions in the assessment of their mechanical and thermal insulation properties. Moreover, the optimal rubber content in the composite is unknown. The presented work addresses these gaps. The research objectives include the development and analysis of new materials based on unsaturated polyester with justification for the required proportion of rubber waste.

Materials and Methods. During the processing of tire rubber, a multistage grinding process was carried out, followed by magnetic and air separation. A powder with a density of 500 kg/m³ was obtained. The minimum particle size was 0.1 mm, and the maximum was up to 1 mm. The composite matrix was unsaturated polyester with a density of 1160 kg/m³. To fabricate the specimens, 0, 10, 20, 30, 40, and 50% rubber filler were added to it. Stable geometry was achieved through curing at room temperature and subsequent mechanical processing. For each composition, three specimens with an area of 0.021 m² and a thickness of 0.01 m were produced.

Results. The dependence of density, water absorption, and thermal conductivity of the samples on the volume of recycled tire rubber was shown. As its proportion increased, a noticeable decrease in density was recorded: at 0% — 1160 kg/m³; at 10% — 1074.3; at 20% — 1037.2; at 30% — 1017.8; at 40% — 963.7; at 50% — 905. Water absorption dynamics were determined by the weight of the samples after immersion in water. It took more than 8 hours for changes (even minor ones) to occur. The indicator in percentage terms increased from 0.024% to 0.47%, meaning the absolute maximum was <0.5%. As the rubber content increased, thermal conductivity decreased. The value for pure polyester was 0.254854 W/(m·K); for the composite with 10% rubber — 0.2510574; with 20% — 0.245156; with 30% — 0.238484; with 40% — 0.223062; with 50% — 0.207039. All samples withstood a load of 1300 kN.

Discussion. The incorporation of 50% rubber into unsaturated polyester results in a 22% reduction in sample density and a 19% decrease in thermal conductivity, with water absorption remaining under 0.5%. These properties suggest the suitability of the composite as an efficient insulation material, even in environments with elevated humidity. Its high compressive strength (>61.83 MPa) allows for its use in structures subjected to significant loads. Varying the rubber content will provide an optimal balance between mechanical properties and moisture resistance.

Conclusion. This work presents an approach for the sustainable recycling of tires to produce effective insulation materials. Promising directions for future study include investigating composites with larger rubber particles (>1 mm), evaluating their acoustic insulation properties, and assessing their fire resistance and chemical stability.

Keywords: tire recycling, unsaturated polyester, properties of polyester-rubber composites, low-absorption materials

Acknowledgements. The authors would like to thank the team of the Composite Materials Laboratory, Faculty of Mechanical Engineering, Aleppo University, for their technical assistance in conducting the experiments.

For Citation. Antypas IR, Savostina TP. Creating Insulation Materials from Unsaturated Polyester and Recycled Tire Rubber. *Advanced Engineering Research* (*Rostov-on-Don*). 2026;26(1):2199. https://doi.org/10.23947/2687-1653-2026-26-1-2199

Оригинальное эмпирическое исследование

Создание изоляционных материалов из ненасыщенного полиэфира и переработанной шинной резины

И.Р. Антибас✉, **Т.П. Савостина**
Донской государственный технический университет, г. Ростов-на-Дону, Российская Федерация
✉ Imad.antypas@mail.ru

Аннотация

Введение. Утилизация автомобильных шин обычно предполагает их складирование, захоронение или сжигание. Как следствие, загрязняются почва и атмосфера. Ученые давно и активно обсуждают переработку шинной резины как один из подходов к решению экологических проблем. Известно, что использование резиновой крошки в композитах позволяет снизить их массу и теплопроводность. Однако мало изучены материалы с резиноотходами на основе ненасыщенного полиэфира. Есть противоречия в оценке их механических и теплоизоляционных свойств. Кроме того, неизвестно оптимальное содержание резины в композите. Представленная работа восполняет эти пробелы. Цели исследования: создание и анализ новых материалов из ненасыщенного полиэфира с обоснованием необходимой доли резиноотходов.

Материалы и методы. При обработке шинной резины провели многоступенчатое измельчение, магнитную и воздушную сепарацию. Получили порошок плотностью 500 кг/м^3. Минимальная фракция — 0,1 мм, максимальная — до 1 мм. База композита — ненасыщенный полиэфир плотностью 1160 кг/м^3. Для изготовления образцов к нему добавляли 0, 10, 20, 30, 40 и 50 % резинового наполнителя. Стабильной геометрии добивались отверждением при комнатной температуре и механической обработкой. Для каждого состава изготовили по три образца площадью 0,021 м^2 и толщиной 0,01 м.

Результаты исследования. Показана зависимость плотности, водопоглощения и теплопроводности образцов от объема переработанной шинной резины. С увеличением ее доли фиксируется заметное снижение плотности: при 0 % — 1160 кг/м^3; при 10 % — 1074,3; при 20 % — 1037,2; при 30 % — 1017,8; при 40 % — 963,7; при 50 % — 905. Динамику водопоглощения определяли по весу образцов после пребывания в воде. Для изменений (причем несущественных) потребовалось более 8 часов. Показатель в процентном отношении растет с 0,024 до 0,47 %, то есть абсолютный максимум <0,5 %. С увеличением доли резины снижается теплопроводность. Показатель для чистого полиэфира — 0,254854 Вт/(м · К); для композита с 10 % резины — 0,2510574; с 20 % — 0,245156; с 30 % — 0,238484; с 40 % — 0,223,062; с 50 % — 0,207039. Все образцы выдержали нагрузку 1300 кН.

Обсуждение. При добавлении в ненасыщенный полиэфир 50 % резины плотность образца снижается на 22 %, коэффициент теплопроводности — на 19 %, а водопоглощение не превышает 0,5 %. Значит, композит будет хорошим изолирующим материалом даже при повышенной влажности. Высокая прочность на сжатие (>61,83 МПа) позволяет использовать его в конструкциях, испытывающих серьезные нагрузки. Варьирование содержания резины даст оптимальный баланс механических свойств и влагостойкости.

Заключение. Предложено решение для экологичной утилизации шин и создания качественных изоляционных материалов. В перспективе можно изучить более крупные частицы резины (от 1 мм) в композите, звукоизоляционный потенциал таких материалов, их стойкость к огню и химическим веществам.

Ключевые слова: переработка автомобильных шин, ненасыщенный полиэфир, свойства композита из полиэфира и резины, материалы с низким водопоглощением

Благодарности. Авторы выражают благодарность коллективу лаборатории композиционных материалов механического факультета Университета Алеппо за техническую поддержку при проведении экспериментов.

Для цитирования. Антибас И.Р., Савостина Т.П. Создание изоляционных материалов из ненасыщенного полиэфира и переработанной шинной резины. *Advanced Engineering Research* (*Rostov-on-Don*). 2026;26(1):2199. https://doi.org/10.23947/2687-1653-2026-26-1-2199

Introduction. The accumulation of automobile tire waste is a global environmental problem. According to [1], approximately 1.5 billion tires are produced worldwide each year, with over 17 million tons being disposed [1]. It is expected that by 2030, the number of end-of-life tires will reach 1.2 billion units. Currently, a significant portion of discarded tires is sent to landfills. As a result:

– the risks of fires and environmental pollution increase;

– the shortage of cheap insulation materials for construction is exacerbated.

It is known that about 40% of global energy consumption is attributable to the construction sector [2]. The industry has a critical need for effective thermal insulation materials to improve the energy efficiency of buildings. Therefore, the development of innovative composites is essential both for enhancing the recycling of rubber waste and for creating much-needed thermal insulation [2].

Unsaturated polyester was selected as the composite matrix due to its thermosetting properties. When mixed with a curing agent, unsaturated polyester forms a rigid polymer structure, allowing the desired shape and porosity to be imparted to the composition. Rubber waste, in turn, serves as an effective dispersed filler. Incorporating rubber crumb into the composite substantially lowers its thermal conductivity. This reduction is attributed to two factors: firstly, the intrinsically low thermal conductivity of rubber (~0.1–0.2 W/(m·K)), and secondly, its particles, dispersed in the polymer matrix, create additional air cavities and a complex network of so-called “thermal bridges” [3].

There are publications on the use of tire rubber and other industrial waste to create materials with high sound-absorbing properties [4]. In [5], the sound transmission loss of three composite panels was measured: made from waste tire rubber, composite wood board, and particleboard. The conditions under which the use of tire rubber improves sound insulation have been determined.

The University of Wisconsin-Milwaukee studied the use of rubber concrete in railway construction [6]. The authors [6] compared the performance of a rubber suspension to a standard mix and revealed its higher strength and ductility. The research also explored the potential of using this waste-derived material for trench backfilling and filling voids in bridge abutments.

In [7], unsaturated polyester composites containing 5–40% recycled rubber glove filler are investigated. It has been found that the additive increases the impact strength of the compound, but reduces tensile and flexural strength. This is explained by weak rubber adhesion and the formation of pores at high levels.

Study [8] shows how the addition of rubber waste to unsaturated polyester reduces the flexural strength of the base polymer material. The reason is the presence of contaminant particles, which impair the mechanical properties of the mixture. It is further revealed that pre-treatment of the rubber waste enhances material stiffness, while pre-heating the rubber prior to incorporation improves the flexural strength of the resulting composite.

In [9], it is demonstrated that incorporating rubber waste particles of varying sizes into unsaturated polyester yields an insulating material with reduced density, thermal conductivity, and water absorption.

The mechanical properties of unsaturated polyester with different rubber waste loadings are reported in [10]. For example, tensile strength ranges from 1.25 to 22.8 MPa, and compressive strength ranges from 8.25 to 79.5 MPa. Thus, the material described is suitable for insulation applications where high mechanical performance is not required.

Study [11] investigated the effect of incorporating 2–4 mm rubber crumb particles on the compressive strength and elasticity of the composite. Both properties improved, particularly following pre-treatment of the rubber waste with synthetic resins. Under these conditions, compressive strength increased by 12% and elasticity by 40%.

The addition of rubber reduces tensile and flexural strength [10], which is caused by pore formation and weak adhesion at the polymer–rubber interface. However, it simultaneously increases impact toughness [7] and elasticity [11].

The negative impact on strength can be reduced. For this purpose, pre-treating the rubber is recommended. Scientists suggest techniques such as cleaning, heating, or resin treatment. All of these improve adhesion and partially restore the mechanical properties of the compound [11].

Despite active and multifaceted interest from researchers in the topic under consideration, some key questions remain unresolved. It is still unknown, for example, how the properties of composites based on unsaturated polyester depend on the concentration and particle size distribution of rubber waste. This concerns parameters such as thermal conductivity, density, water absorption, and flexural and compressive strength.

No optimization criteria have been developed for the composition required to produce an efficient thermal insulation material for construction. In this case, it is important to balance processability, low thermal conductivity, and mechanical properties suitable for the installation and operation of the structure.

The targeted development of such materials requires a deeper understanding of the processes occurring in the unsaturated polyester–rubber crumb system. It is necessary to examine in detail the formation of the porous structure and the mechanism behind the reduction in thermal conductivity. The presented scientific work aims to address this challenge. The research objectives include the creation and comprehensive study of new composites based on unsaturated polyester, with justification for the required proportion of rubber waste.

Materials and Methods. Polymer insulating composites were prepared through blending rubber waste and unsaturated polyester at different weight ratios. The experimental study was conducted in three consecutive stages.

1. Preparation of raw materials and equipment

This phase assessed the feasibility and efficiency of mechanical recycling of end-of-life tires for producing rubber powder with predefined characteristics. The study included an analysis of the processing steps, parametric monitoring at each stage, and final quality control of the resulting material.

In the raw material preparation phase, steel bead wires were first stripped from the tire sidewalls. Primary size reduction was performed using a shredder operating at 80 rpm for 2 minutes, producing particles in the 50–300 mm range. Subsequent grinding in a rotary crusher at 1500 rpm for 5 minutes further reduced the particle size to 10–50 mm.

A critical step in the preparation process involved separation of the ground material. Ferrous residues were extracted using drum magnetic separators operating at 25 rpm with a magnetic induction of 500 mT. Textile fibers were subsequently removed by means of vortex air classifiers operating at an airflow velocity of 15 m/s and a material feed angle of 30°.

The cleaned rubber feedstock was further processed in a roll granulator, yielding granules in the 1–10 mm size range. Subsequently, the material was subjected to fine milling in a ball mill operating at 45 rpm for 60 minutes to achieve a homogeneous powder.

The multistage grinding and separation process yielded a homogeneous rubber powder with a bulk density of 500 kg/m^3. Sieve analysis was conducted to verify its particle size distribution. The results confirmed that all particles were smaller than 1 mm (Table 1), meeting the specified maximum particle size. Notably, 85% of the particles were found to be below 0.37 mm, indicating a predominantly fine-grained fraction suitable for composite fabrication.

Table 1

Sieve Analysis Results for Rubber Powder

Sieve passage of powder, %	100	99.5	99	98	97	95	92	85	30	15	5
Sieve cell, mm	1.0	0.91	0.82	0.73	0.64	0.55	0.46	0.37	0.28	0.19	0.10

Unsaturated polyester resin supplied by SABIC (Saudi Arabia) served as the polymer matrix. The material, a pinkish transparent liquid with a characteristic pungent odor, cured at ambient temperature upon initiator addition. Its density, determined at 25±2°C, was found to be 1160 kg/m^3.

Methyl ethyl ketone peroxide (MEKP) produced by Haihang Industry (China) was used as a polymerization initiator.

2. Specimen fabrication

Test specimens were prepared using silicone molds, which allowed for convenient demolding after curing. The mold cavity dimensions of 145 mm × 145 mm × 10 mm were selected to comply with ASTM D695 standard requirements while also matching the measurement capabilities of the available testing instrumentation.

The volumes of rubber waste in the specimens were 0, 10, 20, 30, 40 and 50%.

Following demolding, all specimens were surface-ground for dimensional stability and eliminating any surface irregularities.

For each composition (0, 10, 20, 30, 40, and 50 vol.% rubber waste), three replicate specimens were prepared and tested to ensure statistically reliable results.

3. Testing

In accordance with international standards, a series of physical, thermal, and mechanical tests were conducted at the Composite Materials Laboratory of the Faculty of Mechanical Engineering, University of Aleppo.

3.1. Physical tests

Specimen density was measured in accordance with ISO 1183-1:2019. The standardized procedure comprised four key steps. During the preparatory stage, appropriate equipment was selected and specimens were conditioned for testing. At the experimental stage, direct mass and volume measurements were conducted. Specimen mass was determined using a balance with a precision of 0.01 g.

Linear dimensions — length, width, and height — were measured using a hardened stainless steel digital caliper with a precision of 0.01 mm.

Specimen volume was determined from the geometric measurements. Density was calculated according to the formula: $\rho = m/V$, where m — specimen mass, V — its volume.

3.2. Water absorption test (ISO 62:2008)

Specimens were submerged in water for 24 hours, with weight measurements recorded at two-hour intervals. Water absorption was calculated from the formula:

$$WR\% = \frac{W - W_1}{W_1} \cdot 100,$$

where W — wet specimen mass after immersion, g; W_1 — dry specimen mass before immersion, g.

3.3. Thermal conductivity test (ISO 8301:1991)

Thermal conductivity measurements were performed using a DRX thermal conductivity analyzer (China). The instrument has a measurement range of 0.01 to 2 W/(m·K) and an accuracy of ±3%. Testing was carried out over a temperature range of 15–100°C, following the Chinese standard GB/T 10295-2008, which corresponds to ISO 8301:1991.

During testing, the heat source was supplied with a constant voltage of 8 V, maintaining a current of 1.18 A and a source temperature of 15°C. Temperature measurements were taken at equal time intervals throughout the experiment. The thermal conductivity coefficient was determined according to Fourier's law:

$$Q = P = \frac{dH}{dt} = V \cdot I = \frac{k \cdot A \cdot \Delta T}{d} \Rightarrow k = \frac{V \cdot I \cdot d}{A \cdot \Delta T},$$

where Q — heat flux; P — thermal power, W; d — specimen thickness, m; H — enthalpy, J; t — time; V — heater supply voltage, V; I — current from the voltage source, A; k — thermal conductivity coefficient, W/(m·K); A — specimen surface area, m^2; ΔT — temperature difference between specimen surfaces, K.

Prior to testing, the thermal conductivity analyzer was calibrated using reference specimens provided by the manufacturer. For each standard specimen, the correlation between nominal (theoretical) and measured thermal conductivity values was established. This allowed for the derivation of a calibration equation and subsequent correction of the experimental thermal conductivity data (Fig. 1).

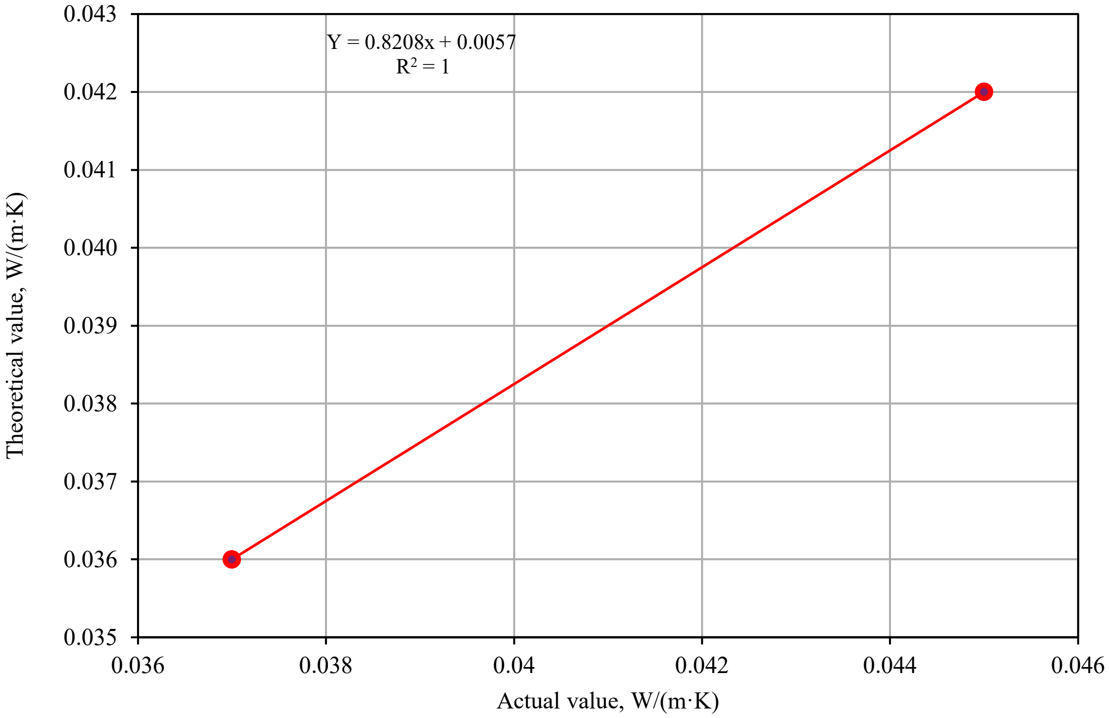

Fig. 1. Calibration curve of the thermal conductivity measuring device: R — coefficient of determination; Y — theoretical thermal conductivity; x — actual value

3.4. Compression testing (ISO 604:2002)

A brief description of the compression testing machine operation is as follows. The upper movable plate applies pressure to square specimens (25 mm thick) placed on the lower plate. The axial load is gradually increased.

Research Results. The density of the specimens was calculated from their mass and volume (Table 2). The obtained data allowed for an analysis of density variation as a function of composition and the physical-mechanical characteristics of the material.

Table 2

Specimen Density Calculation Results

Rubber waste volume, %	Specimen parameters			Density, kg/m^3
	Dry mass, kg·10^{-3}	Area, m^2	Thickness, m	
0	232.00	0.021	0.01	1160
10	225.60			1074.333
20	217.52			1037.238
30	213.73			1017.761
40	202.59			963.714
50	190.06			905.047

Figure 2 shows the density of the specimens as a function of rubber volume fraction.

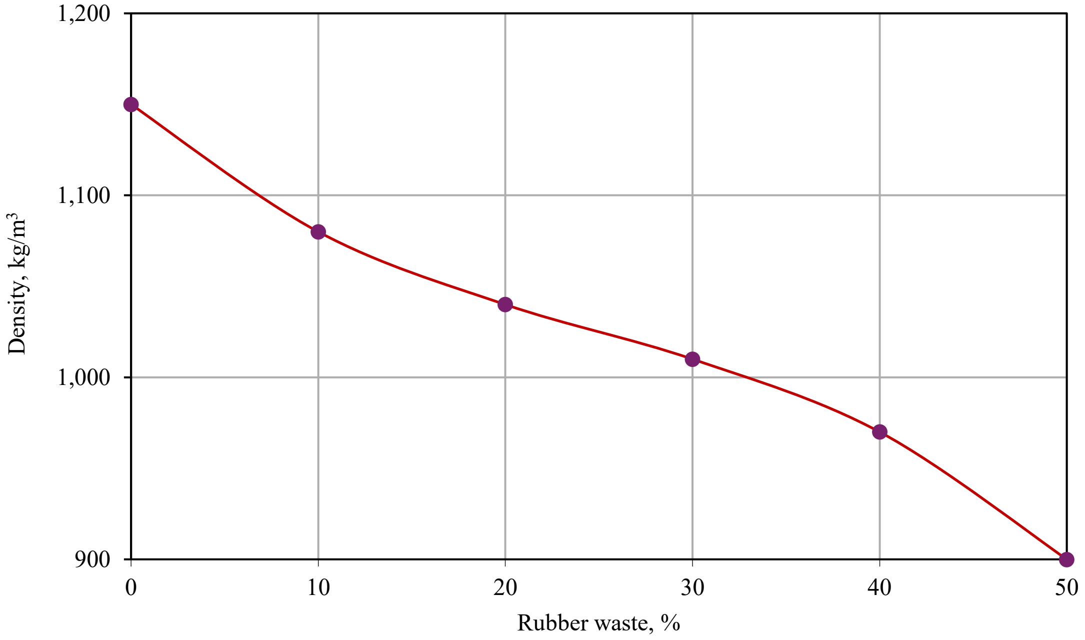

Fig. 2. Density as a function of rubber content

Water absorption behavior was evaluated through monitoring the weight change of specimens after 2 to 24 hours of immersion in water (Table 3).

Table 3

Specimen Water Absorption Behavior

Rubber waste volume, %	Weight before immersion, $k\cdot10^{-3}$	Weight after immersion, $kg\cdot10^{-3}$				
		in 2 hours	in 4 hours	in 6 hours	in 8 hours	in 24 hours
0	201.47	201.47	201.47	201.47	201.50	201.52
10	271.39	271.39	271.40	271.47	271.49	271.66
20	289.14	289.18	289.19	289.26	289.34	289.76
30	287.81	287.86	287.99	288.03	288.06	288.60
40	304.66	304.71	304.83	304.94	304.97	305.56
50	271.78	271.18	272.18	272.28	272.39	273.08

Figure 3 shows water absorption as a function of rubber volume fraction.

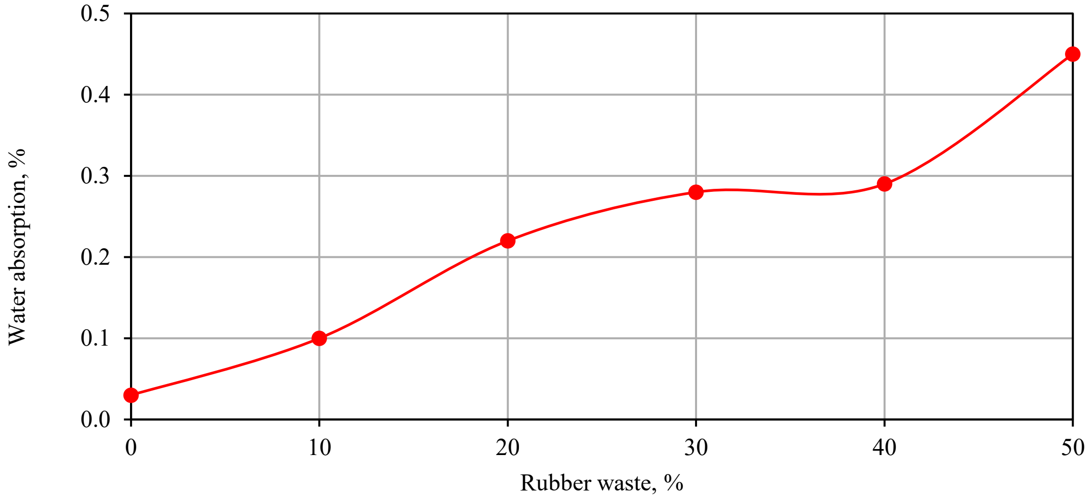

Fig. 3. Dependence of water absorption on rubber loading

Table 4 presents the results of measuring the thermal conductivity coefficient of the specimens.

Table 4

Thermal Conductivity Measurement Results

Rubber waste volume, %	Heat flow, $V \cdot I$, W	Temperature,°C	Specimen area, m^2	Specimen thickness, m	Thermal conductivity coefficient, W/(m·K)
0	8·1.15	17.90	0.021	0.01	0.2548540
10		17.45			0.2510574
20		17.78			0.2451560
30		18.37			0.2384840
40		19.64			0.2230620
50		21.16			0.2070390

Figure 4 shows the thermal conductivity coefficient as a function of rubber waste content.

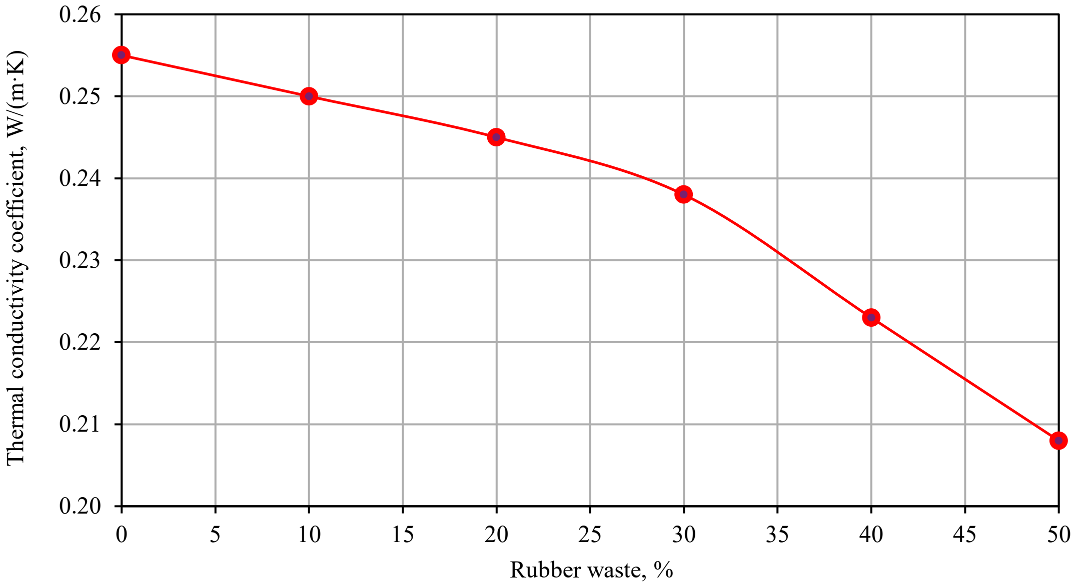

Fig. 4. Thermal conductivity as a function of rubber content

Table 5 shows the compression test results.

Table 5

Compression Test Results

Rubber waste volume, %	Specimen area, m^2	Maximum load, kN	Maximum compressive stress, MPa
0	0.145·0.145	1300	61.83
10			
20			
30			
40			
50			

Discussion. As shown in Table 2 and Figure 2, specimen density decreases as the rubber waste content increases. This is because the rubber has a lower density (500 kg/m^3) than unsaturated polyester (1160 kg/m^3). The specimen with 50% rubber waste exhibited the lowest density (905.05 kg/m^3), representing a reduction of nearly 22% compared to the pure polymer. This density reduction corresponds to a decrease in specimen mass from 232 g to 190 g, with the geometric dimensions held constant (thickness: 0.01 m; area: 0.021 m^2).

The discrepancies between the present results and those reported in [10] are minor and can be attributed to differences in the characteristics of the polymer matrix and the recycled tire rubber [12]. These findings confirm that rubber waste serves as an efficient filler. It allows for a reduction in composite weight and controlled adjustment of the final density to meet specific performance requirements.

As shown in Table 3, specimen mass remained virtually unchanged during the first hours following water immersion. Detectable changes occurred only after 8–24 hours of exposure. Figure 3 demonstrated that incorporating rubber waste into the unsaturated polyester matrix did not substantially affect water absorption in absolute terms. The values increased marginally from 0.024% for pure polyester to a maximum of 0.47% for the composition with 50% rubber waste. Thus, water absorption below 0.5% can be regarded as negligible. In this case, the low water absorption can be attributed to two factors:

– hydrophobic nature of rubber relative to unsaturated polyester;
– microscopic pores formed during the mixing process.

The low water absorption makes these materials promising for applications requiring moisture resistance, such as protective coatings, thermal insulation, and machinery components exposed to humid conditions. Further enhancement of performance could be achieved through chemical surface modification of the rubber particles or by limiting the rubber content to 20–30%, thereby attaining an optimal balance between mechanical integrity and moisture resistance.

According to Table 4 and Figure 4, increasing the rubber waste content to 50% reduces the thermal conductivity coefficient by approximately 19%, thereby enhancing the thermal insulation performance of the specimens. This trend is attributed to the inherently low thermal conductivity of rubber. The composite with 50% rubber waste exhibits a thermal conductivity of 0.2070 W/(m·K), which lies within the range of values reported in previous comparative studies [10]. Minor discrepancies between the present results and those in the literature may arise from differences in measurement techniques or the specific characteristics of the materials employed [13, 14].

Compression testing (Table 5) did not yield precise compressive strength values for the developed composites, as all specimens remained intact up to the maximum load capacity of the testing machine (1300 kN). The corresponding compressive stress at this load was calculated to be 61.83 MPa, which was considered to fall within the acceptable strength range for insulation materials.

Conclusion. This study shows that the incorporation of rubber waste into unsaturated polyester yields composites with enhanced properties suitable for construction applications.

The composition with 50% rubber waste was identified as optimal, exhibiting reduced density and thermal conductivity — key characteristics for thermal insulation materials. Although water absorption increased marginally with higher rubber content, it remained at a very low level (maximum 0.47%), making the composite suitable for use in humid environments.

The tests confirmed the high mechanical strength of the developed composites. All specimens withstood compressive loads of up to 1300 kN without failure, indicating their suitability for use in structural components exposed to mechanical stress.

Thus, the developed composites can contribute to solving two problems:

– environmentally sustainable disposal of substantial quantities of rubber waste;
– fabrication of efficient thermal insulation materials with high structural integrity.

Future work will focus on three main aspects.

1. Investigation of the effect of larger rubber particles (from 1 mm) on the properties of composites.
2. Evaluation of the sound insulation potential of the materials. This requires studying the microstructure, clarifying the proportion of air voids, and their effect on acoustics and mechanical properties.
3. Conducting experiments to study the resistance of the specimens to fire and chemicals.

References

1. Hashamfirooz M, Dehghani MH, Khanizadeh M, Aghaei M, Bashardoost P, Hassanvand MS, et al. A Systematic Review of the Environmental and Health Effects of Waste Tires Recycling. *Heliyon*. 2025;11(2):e41909. https://doi.org/10.1016/j.heliyon.2025.e41909

2. Antipas IR. Effect of Glass Fiber Reinforcement on the Mechanical Properties of Polyester Composites. *Advanced Engineering Research* (*Rostov-on-Don*). 2023;23(4):387–397. https://doi.org/10.23947/2687-1653-2023-23-4-387-397

3. Van de Lindt JW, Carraro JAH, Heyliger PR, Choi C. Application and Feasibility of Coal Fly Ash and Scrap Tire Fiber as Wood Wall Insulation Supplements in Residential Buildings. *Resources, Conservation and Recycling.* 2008;52(10):1235–1240. https://doi.org/10.1016/j.resconrec.2008.07.004

4. Fedoseev IV, Barkan MSh, Prokhotsky YuM, Laskina NE, Loginova AYu. Technology for Recycling Waste Rubber Products. *ChemChemTech*. 2013;56(2):117–120. (In Russ.)

5. Zhao J, Wang X-M, Chang JM, Yao Y, Cui Q. Sound Insulation Property of Wood-Waste Tire Rubber Composite. *Composites Science and Technology*. 2010;70(14):2033–2038. https://doi.org/10.1016/j.compscitech.2010.03.015

6. Siddique R, Naik TR. Properties of Concrete Containing Scrap-Tire Rubber — An Overview. *Waste Management*. 2004;24(6):563–569. https://doi.org/10.1016/j.wasman.2004.01.006

7. Nuzaimah M, Saruan SM, Nadlene N, Jawaid M. Microstructure and Mechanical Properties of Unsaturated Polyester Composites Filled with Waste Rubber Glove Crumbs. *Fibers and Polymers.* 2019;20(6):1290–1300.

8. Paulo JRO Nóvoa, Antonio Ferreira, António Torres Marques. Mechanical Performance of Unsaturated Polyester Resins. *Materials Science Forum.* 2006;514–516:662–665. https://doi.org/10.4028/www.scientific.net/MSF.514-516.662

9. Abu-Jdayil B, Mourad A-H, Hussain A. Thermal and Physical Characteristics of Polyester-Scrap Tire Composites. *Construction and Building Materials.* 2016;105:472–479. https://doi.org/10.1016/j.conbuildmat.2015.12.180

10. Abu-Jdayil B, Mourad A-H, Hussain A. Investigation on the Mechanical Behavior of Polyester-Scrap Tire Composites. *Construction and Building Materials.* 2016;127:896–903. https://doi.org/10.1016/j.conbuildmat.2016.09.138

11. Hanbing Liu, Xianqiang Wang, Yubo Jiao, Tao Sha. Experimental Investigation of the Mechanical and Durability Properties of Crumb Rubber Concrete. *Materials.* 2016;9(3):172. https://doi.org/10.3390/ma9030172

12. Abo Elenien KF, Azab NA, Bassioni G, Abdellatif MH. The Effect of Tire Rubber Particles on the Mechanical and Physical Properties of Polyester. *IOP Conference Series: Materials Science and Engineering.* 2020;973:012019. https://doi.org/10.1088/1757-899X/973/1/012019

13. Fedroff D, Ahmad S, Savas BZ. Mechanical Properties of Concrete with Ground Waste Tire Rrubber. *Transportation Research Record: Journal of Transportation Research Board.* 1996;1532(1):66–72. https://doi.org/10.1177/0361198196153200110

14. Rybak AT, Teplyakova SV, Olshevskaya AV, Prutskov AS. A Method for Monitoring the Reliability of Technical Systems by Identifying the Entropy of the Causes of Their Failures. *Advanced Engineering Research (Rostov-on-Don).* 2025;25(2):112–119. https://doi.org/10.23947/2687-1653-2025-25-2-112-119

About the Authors:

Imad Rizakalla Antipas, Cand.Sci. (Eng.), Associate Professor of the Fundamentals of Machinery Design Department, Don State Technical University (1, Gagarin sq., Rostov-on-Don, 344003, Russian Federation), SPIN-code, ORCID, ScopusID, ResearchID, imad.antypas@mail.ru

Tatyana P. Savostina, Senior Lecturer of the Fundamentals of Machinery Design Department, Don State Technical University (1, Gagarin sq., Rostov-on-Don, 344003, Russian Federation), SPIN-code, ORCID, ScopusID, kovtanya@yandex.ru

Claimed Contributorship:

IR Antipas: conceptualization, data curation, formal analysis, investigation, methodology, resources, supervision, validation, visualization, writing – original draft preparation, writing — review & editing.

TP Savostina: project administration, visualization, writing — original draft preparation,

Conflict of Interest Statement: **the authors declare no conflict of interest.**

All authors have read and approved the final version of the manuscript.

Об авторах:

Имад Ризакалла Антибас, кандидат технических наук, доцент кафедры «Основы конструирования машин» Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1), SPIN-код, ORCID, ScopusID, ResearchID, imad.antypas@mail.ru

Татьяна Петровна Савостина, старший преподаватель кафедры «Основы конструирования машин» Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1), SPIN-код, ORCID, ScopusID, kovtanya@yandex.ru

Заявленный вклад авторов:

И.Р. Антибас: разработка концепции, курирование данных, формальный анализ, проведение исследования, разработка методологии, предоставление ресурсов, научное руководство, валидация результатов, визуализация, написание черновика рукописи, написание рукописи — внесение замечаний и исправлений.

Т.П. Савостина: административное руководство исследовательским проектом, визуализация, написание черновика рукописи.

Конфликт интересов: **авторы заявляют об отсутствии конфликта интересов.**

Все авторы прочитали и одобрили окончательный вариант рукописи.

Received / Поступила в редакцию 25.12.2025
Reviewed / Поступила после рецензирования 20.01.2026
Accepted / Принята к публикации 27.01.2026