Primljen / Received: 10.4.2026.
Ispravljen / Corrected: 13.7.2026.
Prihvaćen / Accepted: 16.7.2026.
Dostupno online / Available online: 10.9.2026.

Physical and mechanical properties of insulation boards with a significant recycled content for underfloor heating and cooling applications

Authors:

Rene Kelemen, MCE
University of Zagreb
Faculty of Civil Engineering
rene.kelemen@grad.unizg.hr
Corresponding author

Domagoj Tkalčić, MCE
University of Zagreb
Faculty of Civil Engineering
domagoj.tkalcic@grad.unizg.hr

Assoc.Prof. **Bojan Milovanović**, PhD. CE
University of Zagreb
Faculty of Civil Engineering
bojan.milovanovic@grad.unizg.hr

Marko Mudrinić, MCE
Plastform d.o.o.
marko.mudrinic@plastform.hr

Original research paper

Rene Kelemen, Domagoj Tkalčić, Bojan Milovanović, Marko Mudrinić

Physical and mechanical properties of insulation boards with a significant recycled content for underfloor heating and cooling applications

This paper investigates the physical and mechanical properties of EPS insulation boards with different shares of recycled material from two sources (construction and packaging). The influence of recycled content on density, thermal conductivity, compressive strength at 10 % deformation, flexural strength, and tensile strength was analysed. The results show a decrease in density and mechanical properties, and an increase in thermal conductivity with increasing recycled content. A non-linear behaviour depending on material structure was observed. The results indicate the potential application of recycled EPS in underfloor heating and cooling systems, with limitations at higher recycled content.

Key words:

expanded polystyrene, recycled EPS, physical properties, mechanical properties, underfloor heating and cooling boards

Izvorni znanstveni rad

Rene Kelemen, Domagoj Tkalčić, Bojan Milovanović, Marko Mudrinić

Fizikalna i mehanička svojstva izolacijskih ploča sa značajnim udjelom reciklata za podno grijanje i hlađenje

U radu su ispitana fizikalna i mehanička svojstva EPS izolacijskih ploča s različitim udjelom recikliranog materijala iz dvaju izvora (građevinski i ambalažni). Analiziran je utjecaj udjela reciklata na gustoću, toplinsku provodljivost, tlačnu čvrstoću pri 10 % deformacije, savojnu i vlačnu čvrstoću. Rezultati pokazuju smanjenje gustoće i mehaničkih svojstava te porast toplinske provodljivosti s povećanjem udjela reciklata. Uočeno je nelinearno ponašanje ovisno o strukturi materijala. Dobiveni rezultati upućuju na mogućnost primjene recikliranog EPS-a u podnim pločama za grijanje i hlađenje, uz ograničenja pri većim udjelima reciklata.

Ključne riječi:

ekspandirani polistiren, reciklirani EPS, fizikalna svojstva, mehanička svojstva, ploče za podno grijanje i hlađenje

1. Introduction

Expanded polystyrene (EPS) is widely used in construction and packaging industries because of its low density, good thermal insulation properties, ease of processing, and low cost [1]. In construction, it is employed as a thermal insulation material in various products and systems. In the packaging industry, it is used to protect foods, electronic equipment, and other sensitive products [12, 13]. However, as a result of these applications, EPS occurs in different waste streams. In particular, construction and packaging EPS may differ considerably in terms of origin, material condition, level of contamination, and potential for reprocessing. Construction EPS most commonly becomes waste during the production, installation, or removal of existing construction products [11, 14]. Depending on its origin, this EPS may be relatively clean, for example, when it consists of production waste or unused material, but it may also be contaminated with other construction layers after long-term use [14]. Packaging EPS, on the other hand, generally enters waste streams more quickly after use. However, its properties may be altered by service conditions, contamination, and previous mechanical damage. Therefore, the origin of the recycled EPS may have an important effect on the properties of the new products in which it is incorporated.

Considering the widespread use of EPS as a packaging material, significant quantities are wasted within a relatively short period after its use. Of the total amount of plastic waste (4,440 kt), 61 % (2,692 kt) came from the packaging sector, and 8 % (372 kt) came from the construction sector. Compared to the approximately 42 kt of EPS/XPS waste generated within the construction sector, considerably larger quantities of material enter the waste management system through the packaging sector [11]. Unlike packaging EPS, construction EPS remains an integral part of a construction product or system after installation. Therefore, it generally enters the waste management system at a later stage. Furthermore, waste generated during the installation of EPS must also be considered, including the waste produced by cutting and fitting boards directly on the construction site.

The challenge of EPS disposal arises from its chemical stability, nonbiodegradability, and low density, which means that it occupies a large volume of waste management systems. Because EPS consists of approximately 98 % air and 2 % polystyrene [15], its disposal is linked to the broader challenges of plastic waste management in the European Union. In 2018, the European Commission adopted the European Strategy for Plastics in a Circular Economy, which laid the foundations for reducing plastic pollution [16]. This strategy emphasises the transition to a circular economy, recycling of plastic packaging, and a reduction in the use of single-use plastics [16].

In this context, standards are being developed to promote product design with a focus on recyclability. The standard HRN EN 18092:2025, *Design-for-recycling guidelines for plastic construction products –Insulation products of expanded polystyrene (EPS)* [14] establishes the principles of the design-for-recycling approach, including recyclability criteria and recommendations for the use of energy-efficient recycling processes, with particular emphasis on mechanical recycling.

According to the 2022 annual work programme for European standardisation, the intention is to increase the proportion of recycled materials in external thermal insulation composite systems (ETICSs) [17]. The EU Taxonomy aims to achieve a recycling rate of 70 % [18]. Member States or regions have already introduced requirements concerning recycled content or intend to do so.

Despite these objectives, according to the current quality guidelines issued by IVH [19] and FV-WDVS [20], and the DIN 4108-10 standards [21], the recycled EPS content in construction products generally ranges from 0 to 19 % by mass. The limited availability of reliable data on the physical and mechanical properties of EPS containing higher proportions of recycled EPS is one reason for this range. Therefore, an experimental programme also included a recycled content of 50 % to assess the effect of a higher recycled material content on product properties.

Although recycled EPS is already being utilized in certain construction products, the available data on the physical and mechanical properties of EPS boards containing higher proportions of recycled materials remain limited, particularly when recycled materials from different sources are compared. This is important because the construction and packaging EPS may differ in terms of material condition, degree of damage, and possible contamination, which may affect the properties of new products. Therefore, this study analysed the effects of the proportion and origin of recycled EPS on the physical and mechanical properties of insulation boards intended for use in underfloor heating and cooling systems.

On this basis, the recEPS project, *Development of an innovative insulation board with a significant proportion of recycled material for underfloor heating and cooling* [22], was developed to reduce the environmental impact through the use of recycled material in the production of insulation boards. The project included tests for density, compressive strength at 10 % deformation, flexural strength, tensile strength, and thermal conductivity.

This study aimed to investigate the physical and mechanical properties of EPS containing different proportions of recycled material from two sources, each of which contained fractions of different densities. The obtained properties were compared with those of virgin EPS containing no recycled material (0 % recycled content).

2. State of the art

Recycling of EPS insulation materials, particularly packaging materials, has been widely reported. Production waste and sorted offcuts from construction sites can be reused in the production of EPS insulation materials. The amount of recycled material used in production considerably depends on the requirements of the intended application. The material used in ETICSs is contaminated with rendered and reinforcing mesh on the outer side and with filler and adhesive on the inner side. Such material cannot be processed into high-quality products for ETICS applications.

According to the quality guidelines of the German Association of Rigid Foam Manufacturers (IVH) and the German Association for External Thermal Insulation Composite Systems (FV-WDVS), the recycled EPS content in façade insulation boards must not exceed 5 % by mass [23]. In applications with less stringent technical requirements, considerably larger amounts of recycled material are sometimes permitted or used. Examples include:

- 20 wt % in DEO-type floor insulation (internal insulation below screed without acoustic insulation requirements) according to DIN 4108-10 [24].
- 20 wt % in DAA-type insulation boards for flat roofs (external roof or ceiling insulation exposed to weather conditions and installed below the waterproofing layer) according to DIN 4108-10 [24].
- According to DIN 4108-10, recycled EPS boards can contain up to 100 wt % recycled granules for DEO-type floor insulation; drainage boards for perimeter insulation with a thermal conductivity level of up to 0.035 W/(m·K); and applications involving internal wall insulation (WI), internal insulation (DI), and insulation between rafters (DZ) [24].
- Loose recycled granules can be used as levelling fill or as a filler/lightweight aggregate to increase the porosity of bricks [25].

Polystyrene insulation materials currently entering the waste stream generally contain the brominated flame-retardant HBCD. HBCD is covered by the regulation (EU) 2019/1021 on persistent organic pollutants (POPs) [26]. As this regulation requires that waste containing POPs be permanently removed from the economic cycle and excluded from potential recycling processes, these petroleum-based insulation materials increasingly need to be collected separately and sent for energy recovery or disposal. This is achieved or supported through separate collection required by the Commercial Waste Ordinance. In the future, the material recycling of EPS insulation boards will only be possible using HBCD-free EPS. An example of material recycling is the CreaSolv process [27] which uses organic solvents for the selective extraction of polystyrene. In this process, the polystyrene polymer is separated from HBCD by solvolysis, bromine is recovered, and high-quality PS granules are produced. A CreaSolv pilot plant is located at the ICL-IP Europe facility, which is a flame-retardant additive manufacturer in the Netherlands. However, no industrial-scale CreaSolv plants are currently available because the small quantities of waste make their operation economically inviable [28]. Nevertheless, establishing smaller-capacity pilot plants is desirable to make the best possible use of the considerably increasing volume of ETICS waste expected in the near future. Their implementation requires an optimised logistics concept in which ETICS waste is mechanically processed at the place where it is generated to reduce its volume and then transported to regional CreaSolv processing plants. This requires shorter transportation distances. However, Croatia currently has no waste incineration plants authorised for energy recovery from EPS waste. According to the German Environment Agency, this process completely destroys HBCD, which is classified as a POP [29]. The use of HBCD as a fuel substitute in cement or brick production is illegal because it may not be completely destroyed by combustion during these processes [28].

3. Description of EPS production and recycling processes

EPS is generally composed of foamed (expandable) homopolymers and copolymers of styrene. According to Maul [20], EPS can be classified into particle, extruded, and integral foams. These foams are generally produced from polystyrene that is preformed using blowing agents, which include low-boiling hydrocarbons such as pentane and chemicals that decompose and release gas such as azo compounds. Particle foams are a general term used for foams produced in two stages.

- Pre-expansion: Pre-expanded particles containing 3.5–7 % pentane as a blowing agent are expanded by steam at approximately 90 °C to 20–50 times their original size. The blowing agent evaporates during this process.
- Block foam production: After cooling, the pre-expanded particles (beads) are foamed for a second time in closed moulds using steam at approximately 110–120 °C, causing the beads to fuse into a homogeneous material.

In addition to its extensive use in construction, EPS is widely used in other sectors including automotive, food, agriculture, and healthcare [31–34]. In construction, EPS is most commonly used as thermal insulation in ETICS. However, it is being increasingly used to produce lightweight concrete and composite materials [33, 34]. In the healthcare and food industries, EPS is used for transport packaging, particularly for temperature-sensitive products [32]. It has a similar application in agriculture, where it is used as packaging for plant seedlings [32]. In the automotive industry, EPS is used to manufacture certain moulded vehicle components [31].

Given the widespread use of EPS across various industries, significant quantities of waste are generated, which necessitates effective management. According to a report by the Global EPS Sustainability Alliance [32], EPS is recycled in 72 countries, demonstrating its potential for reuse and sustainability as a material. EPS is currently recycled using three types of processes: mechanical, chemical, and thermal.

3.1. Mechanical recycling

In mechanical recycling, the material is processed without changing its chemical structure This is among the most commonly used methods for recycling EPS waste. The process generally includes sorting, washing, and drying EPS waste, followed by size reduction through crushing or grinding into flakes, granules, or powder [12]. During crushing, the EPS beads are physically damaged and lose their optimal shape, which may reduce their final bulk density. Each mechanical recycling cycle affects the properties of the EPS to some extent and increases the heterogeneity of the material. However, the available literature contains no studies in which the deterioration of properties has been quantified [35]. Nevertheless, studies have shown that the volume of EPS waste can be significantly reduced without a substantial loss of functional properties, enabling its reuse in construction applications, such as lightweight concrete and thermal insulation composites [36, 37]. Compared to chemical and thermal processes, mechanical recycling requires less energy and offers environmental and economic benefits [12].

Mechanically recycled EPS can be reused to produce new EPS products. Ground EPS waste can be processed into granules, which are then re-expanded and used to produce new insulation boards such as floor insulation boards or drainage boards for perimeter insulation [23]. Recycled EPS can also be used as a lightweight aggregate in cement-based composites to produce lightweight concretes with improved thermal insulation properties [36, 37]. Some studies considered the use of recycled EPS in composite construction boards based on gypsum and other mineral binders.

3.2. Chemical recycling

The chemical (tertiary) recycling of EPS involves the depolymerisation of the material into styrene monomer through catalytic processes, causing a change in the chemical structure of the polymer [35]. These processes involve the use of various chemicals to break down EPS, producing smaller molecules in liquid or gaseous form that can be used to produce new fuels and chemicals. Additionally, chemical recycling includes various methods for dissolving EPS in organic or environmentally acceptable solvents, allowing the material to be processed into new products under controlled conditions, as reported by Ugwu and Obele [12].

The dissolution of EPS produces a polystyrene material that can be reused as a secondary raw material for manufacturing of polystyrene products. In practice, recycled polystyrene is often mixed with virgin polystyrene granules to ensure consistent raw material quality and suitable processability during further processing. Certain chemical recycling methods, such as the CreaSolv process [27], enable the selective separation of brominated flame retardants, such as HBCD, from the dissolved polymer. This produces purified polystyrene suitable for reuse in the manufacturing of new products.

The advantages of chemical recycling include high recycling efficiency and low energy requirements compared with mechanical and thermal methods. Its main disadvantages are process complexity, need for specialised knowledge and experience, high costs, and potential environmental risks associated with the chemicals used [35].

3.3. Thermal recycling

Tkalčić et al. [35] stated that pyrolysis and gasification are thermochemical processes used for the depolymerisation of EPS. These methods are sometimes classified as thermal recycling. Pyrolysis enables the treatment of contaminated plastics and converts waste into useful hydrocarbons; however, it requires a high energy input and long reaction times. Gasification converts waste into energy by processing it at very high temperatures, thereby reducing the need for disposal and the associated incineration costs. Thermal recycling not only reduces the volume of EPS waste but also enables energy recovery, and the recovered energy can be used to power other processes in circular economy facilities. Despite these advantages, these methods are generally not considered environmentally acceptable forms of recycling because of their high energy requirements, greenhouse gas emissions, and risk of releasing toxic substances into the air.

4. Experimental programme and materials

4.1. Description of test specimens

We conducted tests on four types of specimens that differed in the composition of the mixtures used to produce them. Specimens designated as S1 were made from a mixture of virgin and construction EPS and specimens designated as S2 were made from a mixture of virgin and packaging EPS. The preparation of mixture S1 involved the mechanical recycling of construction EPS generated as a by-product of thermal insulation production or originating from an unused thermal insulation material. In contrast, at this stage of development, mixture S2 was produced using a clean-packaging EPS intended for agricultural applications that had not previously been used. The aim of this initial stage of product development was to determine whether such a material could be used to produce EPS boards containing recycled material and to examine how its origin and proportion affects the tested properties. The development of a procedure for the preparation and decontamination of post-consumer packaging EPS was not included in this study. Instead, it represents the next stage of product development, providing an opportunity for its further improvement.

After crushing, the recycled material to a resultant average density of 15–17 kg/m^3, it was mixed with virgin EPS having nominal densities of 20 kg/m^3 and 25 kg/m^3. Virgin EPS consisted of uniform closed beads separated by thin membranes, whereas recycled EPS from both sources, S1 and S2, was characterised by cracked and crushed beads. Figures 1 and 2 show the differences between virgin and recycled EPS beads.

Figure 1. Uniform beads of virgin EPS

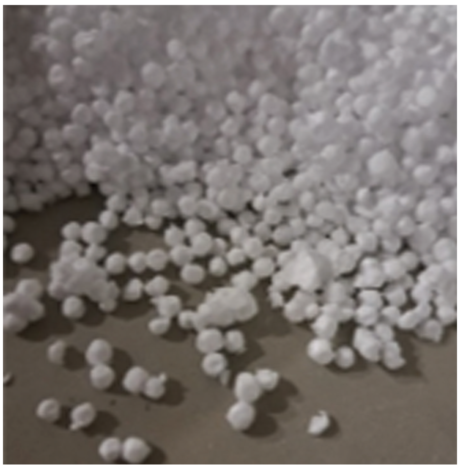

Figure 2. Cracked beads of mechanically recycled EPS

To determine how recycled content affected the tested properties, specimens containing 5 %, 10 %, 25 %, and 50 % recycled materials were produced in addition to reference specimens containing only virgin EPS. This provided two recycled content levels below 20 wt %, which complied with the guidelines specified in DIN 4108-10 [24], and two levels above 20 wt % (25 % and 50 %), which were included to investigate the properties and behaviour of products containing larger amounts of recycled material. Accordingly, the specimen series were designated as follows:

- **Series S1-20** – specimens produced by mixing virgin EPS with a nominal density of 20 kg/m³ and mechanically recycled EPS from source S1
- **Series S1-25** – specimens produced by mixing virgin EPS with a nominal density of 25 kg/m³ and mechanically recycled EPS from source S1
- **Series S2-20** – specimens produced by mixing virgin EPS with a nominal density of 20 kg/m³ and mechanically recycled EPS from source S2
- **Series S2-25** – specimens produced by mixing virgin EPS with a nominal density of 25 kg/m³ and mechanically recycled EPS from source S2.

Eighteen EPS blocks measuring 2600 × 1300 × 1050 mm were produced. Two blocks were made from virgin EPS (0 % recycled content), whereas the remaining 16 blocks were produced by mixing virgin EPS with recycled materials from sources S1 and S2 at volume fractions of 5 %, 10 %, 25 %, and 50 %. The EPS blocks were produced using a standard steam expansion moulding process, in which recycled EPS was homogeneously mixed with pre-expanded virgin beads before moulding. However, because of the irregular shape and damaged structure of the recycled beads, increasing the recycled content reduced the cohesion, consequently decreasing the bulk density, which affected the mechanical and thermal properties.

Three boards measuring 500 mm × 1000 mm × 50 mm were cut from each block using the hot-wire cutting method. The boards were removed from the top, middle, and bottom of the block along a diagonal plane. The selected boards, as shown in Figure 3, represent specific positions within the block. This selection ensured the traceability of specimen locations and enabled the analysis of representative specimens while accounting for the spatial variability of properties within the EPS block.

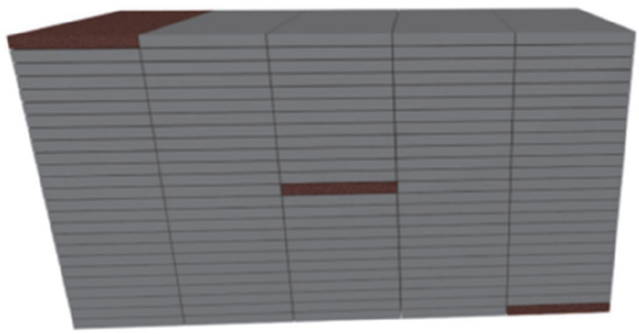

Figure 3. Positions of the boards within the EPS block (top, middle, and bottom).

The specimens used for testing their physical and mechanical properties were obtained from previously cut boards. 54 specimens each were tested to determine density, thermal conductivity, and tensile strength. In addition, 270 and 162 specimens were tested to determine compressive strength at 10 % deformation and flexural strength, respectively.

4.2. Properties tested and the corresponding test methods

Tests were conducted to determine the effects of different proportions of recycled content on the physical and mechanical properties of the EPS. The physical properties tested were density and thermal conductivity, while the tested mechanical properties included compressive strength at 10 % deformation (σ_{10}), flexural strength (σ_b), and tensile strength (σ_t).

All tests were conducted under controlled laboratory conditions at a temperature of 23 ± 2 °C and a relative humidity of 50 ± 5 %, in accordance with the relevant Croatian and European standards.

Table 1. Properties tested

Property tested	Standard	Number of specimens per block	Specimen dimensionsa [mm]
Density	HRN EN ISO 29470:2020 [38]	3	1000 × 500 × 50
Thermal conductivity	HRN EN 12667:2002 [39]	3	300 × 300 × 50
Compressive strength at 10 % deformation	HRN EN ISO 29469:2022 [40]	15	100 × 100 × 50
Flexural strength	HRN EN 12089:2013 [41]	9	300 × 150 × 50
Tensile strength	HRN EN 1607:2013 [42]	3	100 × 100 × 50

Density (ρ) was determined in accordance with HRN EN ISO 29470:2020 [38]. Rectangular specimens measuring 1000 × 500 × 50 mm were weighed using a non-automatic electronic precision balance (Kern PCD10KO). Their lengths, widths, and thicknesses were measured using a Stiro-Lab XYZ.320 measuring table and a Suki 0–150 mm calliper.

Thermal conductivity (λ) was determined for specimens measuring 300 × 300 × 50 mm using the heat flow meter method with a Stiro-Lab LM PLUS 305 apparatus. In accordance with HRN EN 12667 [39], a mean temperature of 10 °C and a temperature difference of 10 °C between the hot and cold plates were used.

A universal testing machine for determining the properties of thermal insulation materials (Excel Didactic, model FS.10), equipped with a 10 kN load cell, was used to test the compressive strength at 10 % deformation (σ_{10}), flexural strength (σ_b), and tensile strength (σ_t).

Compressive strength at 10 % deformation (σ_{10}) was determined on rectangular specimens measuring 100 × 100 × 50 mm. In accordance with the HRN EN ISO 29469 standards, before testing, the specimens were preloaded to a pressure of 250 Pa and then loaded at a constant deformation rate of 10 mm/min [40].

Flexural strength (σ_b) was tested on specimens measuring 300 × 150 × 50 mm, with a support span of 250 mm and a loading rate of 10 mm/min. The test was conducted according to Method B in accordance with HRN EN 12089 [41].

Tensile strength (σ_t) was tested on rectangular specimens measuring 100 × 100 × 50 mm, in accordance with HRN EN 1607 [42].

For each tested property, Table 1 lists the standards according to which the test was conducted, the number of specimens taken from each block, and the dimensions of the tested specimens.

5. Results and discussion

Because the aim was to develop an insulation board for underfloor heating and cooling, the results were also considered in terms of the potential use of this material in the final product. For such boards, it is important to keep thermal conductivity as low as possible while maintaining suitable mechanical properties, particularly compressive strength at 10 % deformation, flexural strength, and tensile strength. This is important because the board used in a flooring system must provide thermal insulation while serving as a stable base for transferring loads through the floor layers.

5.1. Effect of recycled content on the physical properties of the tested specimens

This subsection presents the effects of the recycled content on density and thermal conductivity. The results are presented as bar charts, with the proportion of recycled content in the mixture plotted on the x-axes and the physical properties of the material, density and thermal conductivity, plotted on the y-axes. The vertical lines at the top of each bar represent the standard deviation, indicating the scattering of the measured values around the mean values of that physical property. Relatively low standard deviations indicate good measurement repeatability and specimen homogeneity, whereas the slightly increased scattering at higher recycled contents may be associated with the nonuniform structure of the recycled EPS.

Polynomial trend lines were used to provide a descriptive representation of the changes in properties over the tested range of recycled content values. They should not be interpreted as models for predicting material behaviour beyond the tested values.

Figure 4 shows a general decrease in the density as the recycled content increases. As the change in density with increasing recycled content was not entirely linear, third-order polynomial trend lines are included as descriptive approximations of the experimental data. The corresponding equations and coefficients of determination (R^2) are listed in Table 2. The average density of the recycled materials used (S1 and S2) ranged from 15 to 17 kg/m^3, which was lower than the density of the virgin EPS used in the reference specimens. Therefore, a decrease in the overall material density with increasing recycled content was expected.

At lower recycled content values of up to approximately 10 %, the changes in density were relatively small, amounting to no more than 2 %. A more pronounced decrease was observed at higher recycled content values, particularly between 25 % and 50 %. For example, the density of the S1-25 specimens

Table 2. Trend-line equations and R^2 values for the density of EPS containing recycled material

Specimen designation	Trend-line equation	R^2
S1-20	$y = -0.0017x^3 + 0.0081x^2 - 0.0913x + 20.234$	0.9970
S1-25	$y = 0.0024x^3 - 0.026x^2 - 0.4905x + 26.468$	0.9998
S2-20	$y = 0.0027x^3 - 0.0631x^2 + 0.1686x + 20.168$	0.9670
S2-25	$y = -0.0153x^3 + 0.2033x^2 - 1.0489x + 26.798$	1

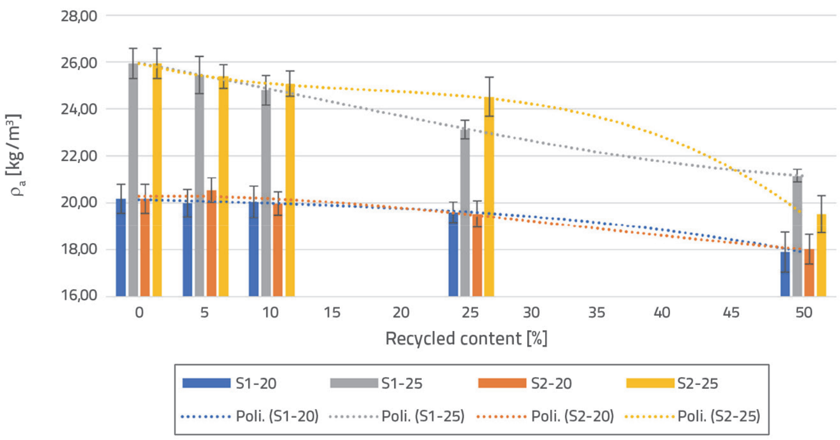

Figure 4. Effect of recycled content on EPS density

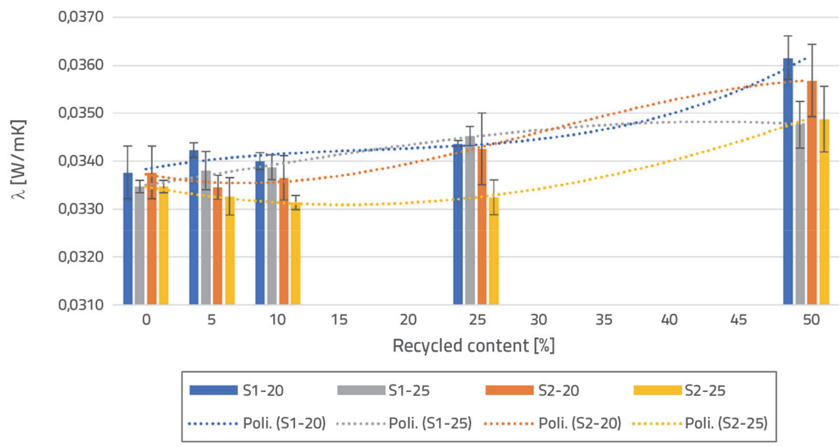

Figure 5. Effect of recycled content on the thermal conductivity of EPS

decreased by 7 % between the specimens containing 10 % and 25 % recycled material. Specimens with a higher initial density (S1-25 and S2-25) maintained a higher absolute density, but also showed a greater relative decrease as the recycled content increased. In contrast, specimens S1-20 and S2-20 exhibited more stable behaviour at low and intermediate recycling contents.

The decrease in density was not caused solely by the lower density of the recycled material, but also by changes in its structure. Mechanical recycling altered the cellular structure of EPS, resulting in nonuniform cell size and distribution, which affects material properties.

Figure 5 shows the effect of the recycled content on the thermal conductivity of EPS. A general increase in thermal conductivity was observed as the recycled content increased, although this trend was nonlinear. At lower recycled contents, the change in thermal conductivity was relatively small, whereas a more pronounced increase was observed at higher contents of 25 % and 50 %. Third-order polynomial trend lines are shown for each EPS formulation to describe the change in thermal conductivity over the tested range of recycled content values. The corresponding equations and coefficients of determination are listed in Table 3.

Superficially, the increase in thermal conductivity with decreasing density may appear unexpected because a higher proportion of air in the material would be expected to reduce heat transfer. However, the overall thermal conductivity of a material results from several heat transfer mechanisms and can be

Table 3. Trend-line equations and R^2 values for the thermal conductivity of EPS containing recycled material

Specimen designation	Trend-line equation	R^2
S1-20	$y = 6 \cdot 10^{-6}x^3 - 7 \cdot 10^{-5}x^2 + 4 \cdot 10^{-4}x + 0.0335$	0.9812
S1-25	$y = -1 \cdot 10^{-6}x^3 + 7 \cdot 10^{-6}x^2 + 2 \cdot 10^{-4}x + 0.0333$	0.9888
S2-20	$y = -6 \cdot 10^{-6}x^3 + 1 \cdot 10^{-4}x^2 - 5 \cdot 10^{-4}x + 0.0341$	0.9939
S2-25	$y = -5 \cdot 10^{-7}x^3 + 5 \cdot 10^{-5}x^2 - 3 \cdot 10^{-4}x + 0.0338$	1

Table 4. Trend-line equations and R^2 values for the measured compressive strength at 10 % deformation of EPS containing recycled material

Specimen designation	Trend-line equation	R^2
S1-20	$y = -0.1926x^2 + 0.1074x + 129.99$	0.9996
S1-25	$y = -0.0603x^3 + 1.2836x^2 - 12.832x + 191.82$	0.9914
S2-20	$y = -0.0236x^3 + 0.3122x^2 - 4.1962x + 135.12$	0.9688
S2-25	$y = -0.0783x^3 + 0.9285x^2 - 7.9281x + 186.06$	0.9999

expressed as the sum of the contributions of the solid phase, gas, radiation, and convection, as shown in Equation (1) [43]:

$$\lambda_{ef} = \lambda_{kruta} + \lambda_{plin} + \lambda_{zračenje} + \lambda_{strujanje} \quad (1)$$

At lower densities, the EPS contained less solid polystyrene, resulting in larger cells and thinner cell walls, which increased the contribution of radiative heat transfer through the cells. This contribution typically increases with the square of the cell diameter, which can significantly increase the thermal conductivities of lower-density materials [43].

Simultaneously, the proportion of the gas phase increased as density decreased. Although air is a good insulator, larger cells provide less resistance to heat transfer through the gas, resulting in higher effective thermal conductivity. In extreme cases, microconvection may also occur within the cells, further increasing heat transfer [43].

In addition, mechanical recycling causes structural irregularities, such as nonuniform cell sizes, cracked cell walls, and a partially open-cell structure. These irregularities disrupt the closed-cell structure, which is a characteristic of virgin EPS, and allow heat to be transferred more readily through the material.

5.2. Effect of recycled content on mechanical properties

The effect of recycled material content on the mechanical properties was analysed in terms of compressive strength at 10 % deformation, flexural strength, and tensile strength. The results are presented as bar charts, with the volume fraction of the recycled content, expressed as a percentage plotted on the x-axes, and the values of the relevant mechanical properties plotted on the y-axes. Each of these charts also includes trend lines showing the changes in the respective mechanical properties as a function of the recycled content. The corresponding trend line equations and coefficients of determination for each series of specimens are listed in table following the chart.

Analysis of the chart in Figure 6 shows that the compressive strength decreased as the recycled material content increased. Quantitatively, for specimens with a lower initial density (S1-20 and S2-20), a recycled content of 50 % resulted in decrease of 16.87 % and 26.58 %, respectively, in the compressive strength at 10 % deformation when compared with the corresponding reference specimens. For specimens with a higher initial densities (S1-25 and S2-25), the decrease in compressive strength was more pronounced, amounting to 29.82 % and 40.31 %, respectively, when the reference specimens were compared with those containing 50 % recycled material. This behaviour is consistent with the previously observed decrease in density, where higher recycled material content resulted in a more pronounced deterioration of the mechanical properties.

The trend curves are shown in the chart. A second-order polynomial function was used for the S1-20 series, whereas third-order polynomial functions were used for the other series. The curves were used to describe the change in the compressive strength over the tested range of recycled content. The corresponding equations and coefficients of determination (R^2) are presented in Table 4.

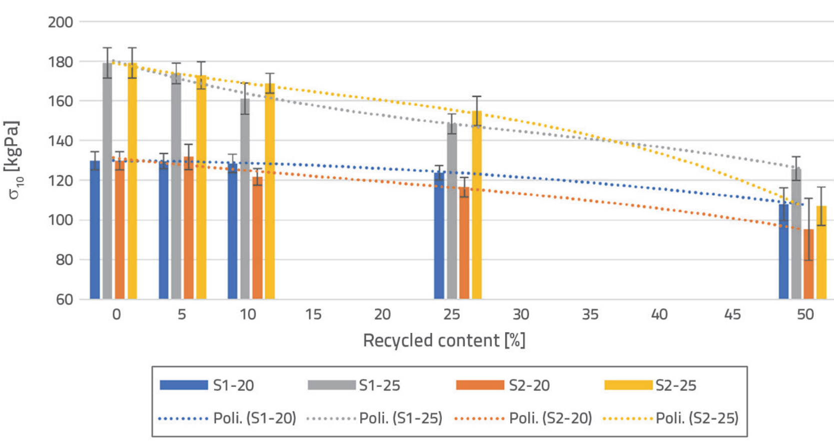

Figure 6. Effect of recycled content on compressive strength at 10 % deformation

In addition to changes in compressive strength, it is important to understand the mechanical response of the material itself. Therefore, the stress–strain curves are analysed next.

As shown in Figure 7, Gibson and Ashby [44] described the behaviour of cellular materials, including EPS, by dividing the stress–strain curve into three characteristic regions: elastic, plateau, and densification regions.

In the initial elastic region, the strain is proportional to the stress, and the slope of this part of the curve corresponds to the initial elastic modulus of the material.

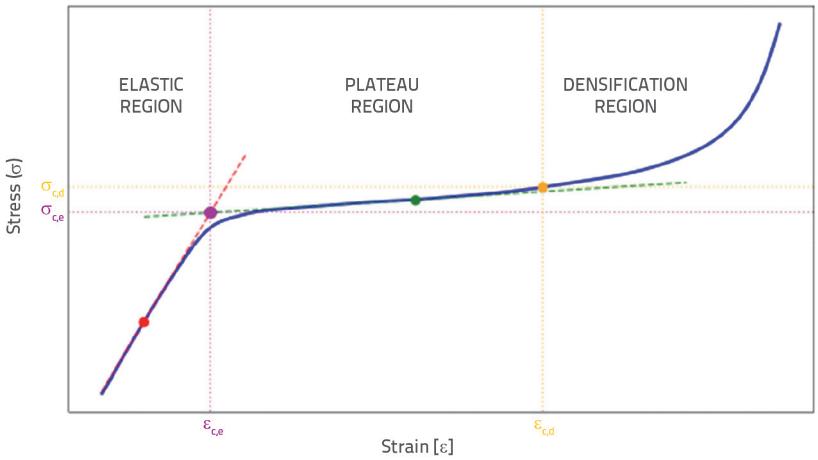

Figure 7. Characteristic stress–strain curve for EPS [44]

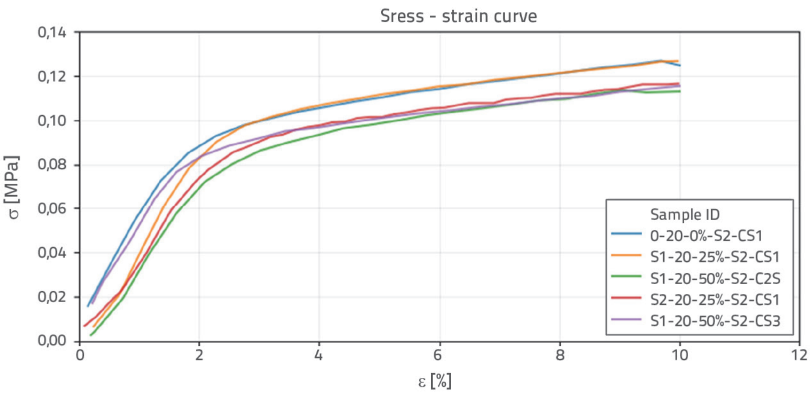

Figure 8. Stress–strain curves obtained for the reference specimen and specimens containing different proportions of recycled EPS

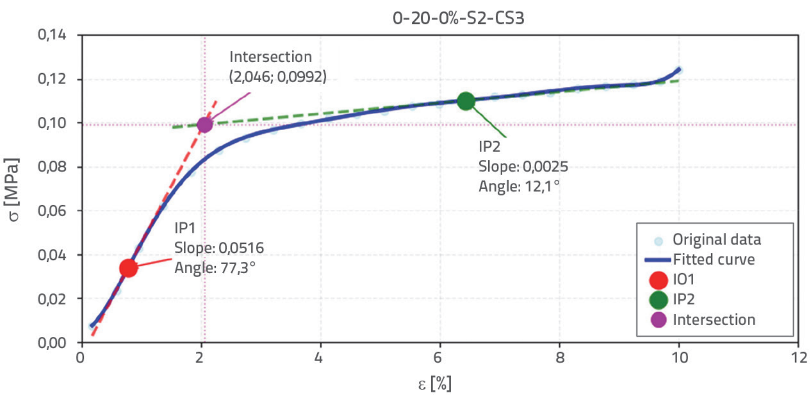

Figure 9. Stress–strain curve obtained for the reference specimen

Deformation in this region is generally reversible and associated with the elastic deformation of the cell walls [44].

This is followed by the plateau region in which the cellular structure gradually collapses through the bending and fracture of the cell walls, with only a relatively small increase in stress as the strain increases. The material absorbs most of the deformation energy in this region [44].

At higher strains, the material enters the densification region, where the collapsed cells are compressed against one another. This reduces the void volume and causes a rapid increase in material stiffness, resulting in a sharp increase in stress [44].

Figure 8 shows the stress–strain curves for the reference specimen and specimens containing different proportions of recycled EPS. A comparison of the curves shows a shift towards lower stress values, whereas the characteristic shape of the stress–strain response remains unchanged.

Figure 9 shows a representative stress–strain curve for the reference specimen, with the tangents indicated in the elastic and plateau regions. The intersection of these tangents defines the transition from elastic to elastic–plastic material behaviour, corresponding to the onset of cellular structure collapse. In the reference specimen, this transition is clearly defined and relatively stable, indicating a homogeneous internal material structure.

Figures 10 and 11 show the stress–strain curves of specimens containing 50 % recycled EPS from construction and packaging sources, respectively. In both cases, the slope of the initial linear portion of the curve decreases, indicating a reduction in the initial modulus of elasticity. This effect was more pronounced in the specimens containing recycled packaging material. Simultaneously, the plateau region became less clearly defined, whereas the transition between the regions showed greater variability, indicating a nonuniform deformation process and an earlier onset of cellular structure collapse.

The tangent slopes in the elastic region (IP1) presented in Tables 5 and 6 exhibit a clear decreasing trend as the recycled material content increases.

For the reference specimens, the tangent slope in the elastic region falls within a narrow range of 0.0516–0.0525. Greater scattering was observed for specimens containing 25 % recycled construction EPS (S1), with values ranging from 0.0439 to 0.0553. At a recycled content of 50 %, these values fell within a more consistent but lower range of approximately 0.044–0.047.

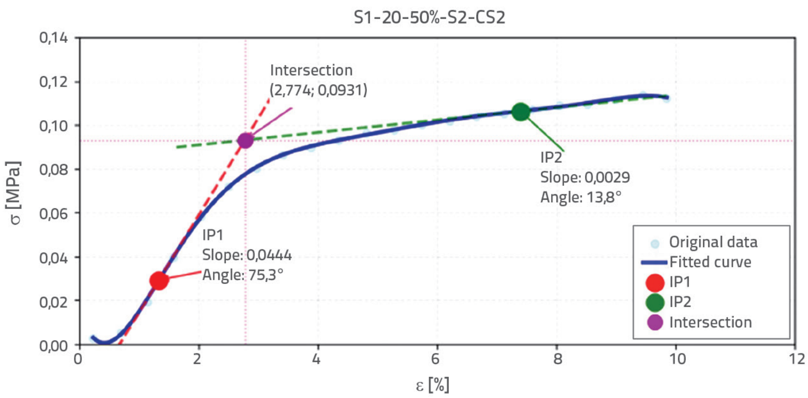

Figure 10. Stress–strain curve obtained for a specimen containing 50 % recycled construction EPS

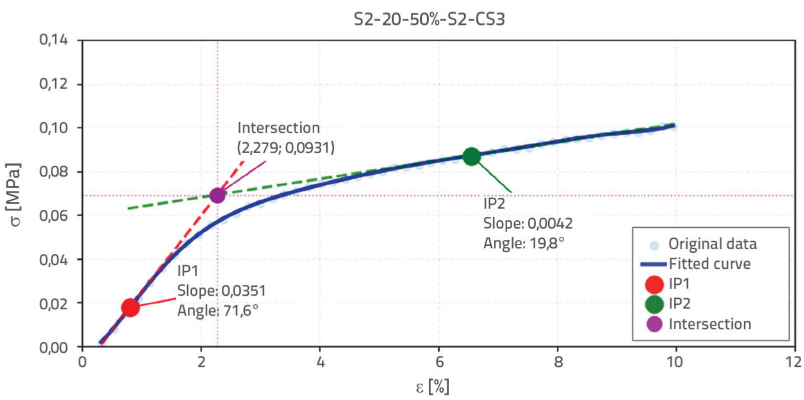

Figure 11. Stress–strain curve obtained for a specimen containing 50 % recycled packaging EPS

For the specimens containing recycled packaging EPS (S2), the decrease in the tangent slope (IP1) was more pronounced. At a recycling content of 25 %, the values decreased to approximately 0.0409–0.0436, whereas at 50 %, they decreased further to approximately 0.0309–0.0351. These results confirmed a greater reduction in the initial modulus of elasticity for recycled packaging EPS than for recycled construction EPS.
Unlike the tangential slopes in the elastic region, the slopes in the plateau region (IP2) did not show a consistent trend. The reference specimens exhibited a relatively wide range of values (0.0025–0.0056). As the recycled content increased, the variability became more pronounced without a clear monotonic trend. For the specimens containing recycled construction EPS, the slopes in the plateau region (IP2) generally decreased slightly. In contrast, specimens containing recycled packaging EPS, particularly at a recycled content of 50 %, showed a local increase in the value, reaching approximately 0.0055.
This behaviour indicated changes in the deformation response of the material within the plateau region. The increased scatter and absence of a clear trend may be associated with the nonuniform collapse of the cellular structure and greater material heterogeneity, particularly in specimens containing recycled packaging EPS.
Next, we present the flexural strength results (Figure 12 and Table 7) and tensile strength results (Figure 13 and Table 8) as functions of the recycled material content. The test results were as follows:
A comparison of the results shows a clear decrease in the flexural strength as the recycled content increases. The highest values were recorded for the reference specimens, whereas the greatest decrease was observed for specimens S1-25 and S2-25.
The decrease in flexural strength was particularly pronounced at higher recycled material contents, particularly at 50 %, where the load-bearing capacity was substantially lower than the reference values. The observed trend was not entirely linear, as indicated by the corresponding polynomial trend curves in Figure 12.

Table 5. Slopes and angles of the IP1 and IP2 tangents to the stress–strain curves obtained for individual specimens containing 0 %, 25 %, and 50 % recycled construction EPS (S1)

Specimen designation	IP1 – slope	IP1 – angle [°]	IP2 – slope	IP2 – angle [°]
REF-1	0.0521	77.4	0.0048	22.4
REF-2	0.0525	77.5	0.0056	25.5
REF-3	0.0516	77.3	0.0025	12.1
S1-25-CS1	0.0553	78.1	0.0049	22.6
S1-25-CS2	0.0483	76.4	0.004	19
S1-25-CS3	0.0439	75.1	0.0027	13.1
S1-50-CS1	0.0474	76.2	0.0038	18
S1-50-CS2	0.0444	75.3	0.0029	13.8
S1-50-CS3	0.0445	75.3	0.0026	12.4

Table 6. Slopes and angles of the IP1 and IP2 tangents to the stress–strain curves obtained for individual specimens containing 0 %, 25 %, and 50 % recycled packaging EPS (S2)

Specimen designation	IP1 – slope	IP1 – angle [°]	IP2 – slope	IP2 – angle [°]
REF-1	0.0521	77.4	0.0048	22.4
REF-2	0.0525	77.5	0.0056	25.5
REF-3	0.0516	77.3	0.0025	12.1
S2-25-CS1	0.0436	75.0	0.0041	19.4
S2-25-CS2	0.0420	74.5	0.0027	13.1
S2-25-CS3	0.0409	74.1	0.0026	12.5
S2-50-CS1	0.0309	69.3	0.0055	25.3
S2-50-CS2	0.0342	71.2	0.0037	17.8
S2-50-CS3	0.0351	71.6	0.0042	19.8

Table 7. Trend-line equations and R^2 values obtained for the flexural strength of EPS containing recycled material

Specimen designation	Trend-line equation	R^2
S1-20	$y = -0.0381x^3 + 0.0822x^2 + 0.9357x + 210$	0.9729
S1-25	$y = 0.0756x^3 - 1.1312x^2 - 9.2313x + 313.35$	0.9994
S2-20	$y = -0.1497x^3 + 2.025x^2 - 10.957x + 219.32$	0.9985
S2-25	$y = -1.263x^2 - 1.1028x + 293.4$	0.9700

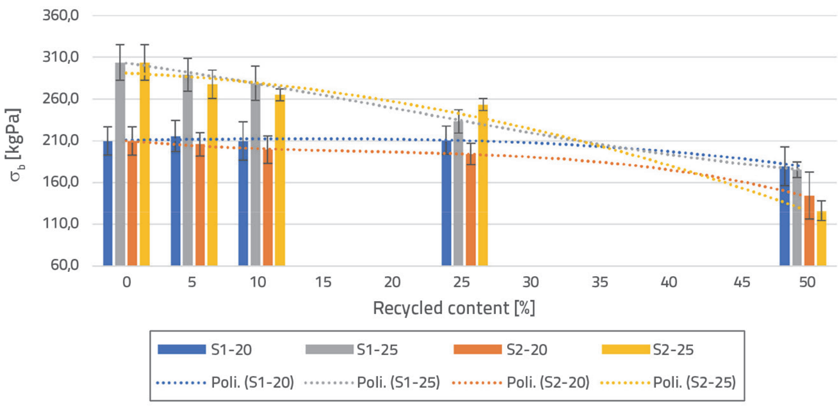

Figure 12. Effect of recycled content on flexural strength

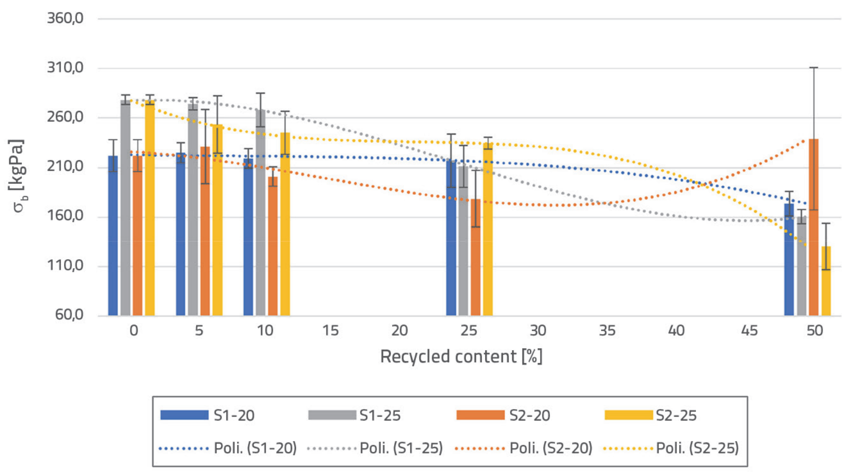

Figure 13. Effect of recycled content on tensile strength

The trend-line equations and coefficients of determination presented in Table 7 agreed well with the experimental data over the tested range ($R^2 \approx 0.97$–0.999). The curves were used to provide a clearer representation of the observed trend and to compare the changes in flexural strength as a function of the recycling content.

The tensile strength results are presented in Figure 13. Similar to flexural strength, a general decreasing trend was observed as the recycled material content increased. For the specimens containing recycled construction EPS (S1), the decrease was gradual. The changes were less pronounced at lower recycled content, whereas a greater reduction in strength was observed at higher content.

For specimens containing recycled packaging EPS (S2), deviations from the general trend were observed, with some specimens exhibiting local increases in strength. This behaviour may be associated with the greater scatter of the results and the potential effects of material heterogeneity or experimental variability, as indicated by the higher standard deviations. The polynomial trend curves shown in the chart indicate a nonlinear change in the tensile strength over the tested range of

Table 8. Trend-line equations and R^2 values obtained for the tensile strength of EPS containing recycled material

Specimen designation	Trend-line equation	R^2
S1-20	$y = -0.0687x^3 + 0.5046x^2 - 1.8432x + 224.42$	0.9921
S1-25	$y = 0.3632x^3 - 6.2281x^2 + 14.762x + 268.7$	0.9994
S2-20	$y = 0.3435x^3 - 3.9651x^2 + 3.2186x + 226.47$	0.9079
S2-25	$y = -0.5086x^3 + 7.9152x^2 - 42.05x + 312.17$	0.9994

recycled content. The coefficients of determination presented in Table 8 ($R^2 \approx 0.9079–0.9994$) indicate the degree of agreement between the fitted curves and the experimental data.

6. Conclusions

This study investigated the physical and mechanical properties of EPS containing different proportions of recycled materials from two sources: construction and packaging EPS. The results were compared with those obtained for reference specimens without recycled material. A general decrease in density was observed as the recycled content increased, although the relationship was nonlinear. At recycled contents of 5 % and 10 %, density decreased by approximately 2 % on average across all series. The average decrease was 6 % and 17 % at recycled contents of 25 % and 50 %, respectively, compared with the corresponding reference specimens. The greatest decrease in density, approximately 25 %, was recorded for the S2-25 series with a recycled content of 50 %. The more pronounced decrease at higher recycled contents may be associated with changes in the cellular structure of the material and the nonuniform size and distribution of the cells.

Simultaneously, the thermal conductivity increased with increasing recycling content, followed by a nonlinear trend. At recycled contents of 5 % and 10 %, deviations in thermal conductivity from the corresponding reference values did not exceed 1.2 %. The average increase was 1.4 % and 5.2 % for recycled contents of 25 % and 50 %, respectively. The greatest increase of 7.1 % was recorded for the S1-20 series with a recycled content of 50 %. This behaviour may be attributed to the changes in the material structure: larger cells and thinner cell walls increase the contribution of radiative heat transfer, whereas structural irregularities allow heat to be transferred more readily through the material.

Regarding the mechanical properties, compressive strength at 10 % deformation decreased as the recycled material content increased. This was accompanied by a reduction in the initial modulus of elasticity, whereas the characteristic shape of the stress–strain curve remained unchanged. At recycled contents of 5 %, 10 %, 25 %, and 50 %, compressive strength decreased by an average of 1.3 %, 5.8 %, 11.4 %, and 28.4 %, respectively, compared to the corresponding reference specimens. The greatest decrease, 40.3 %, was recorded for the S2-25 series with a recycled content of 50 %. Increasing the recycled content also resulted in greater variability within the plateau region, indicating a nonuniform collapse of the cellular structure, particularly in specimens containing recycled packaging EPS.

The flexural and tensile strengths decreased as the recycled material content increased. At the lower recycled contents of 5 % and 10 %, the changes were less pronounced. At a recycling content of 25 %, the average reductions increased to 11.7 % for flexural strength and 16.0 % for tensile strength. The corresponding average reductions at a recycling content of 50 % were 36.5 % and 28.0 %, respectively. The greatest individual decreases were recorded for the S2-25 series, amounting to 58.5 % for flexural strength and 53.1 % for tensile strength. The S2-20 series was an exception; at a recycled content of 50 %, tensile strength increased by 6.3 %, although these results also had the highest standard deviation.

The results showed that changes in density, thermal conductivity, and mechanical properties were smallest for recycled contents of up to 10 %. More pronounced changes in the tested properties occurred at recycled contents of 25 % and particularly 50 %, with greater variability observed for recycled packaging EPS. Therefore, for use in insulation boards for underfloor heating and cooling, the recycled content should be selected to maintain low thermal conductivity and suitable mechanical properties, ensuring a stable base and effective load transfer through the floor layers.

Acknowledgements

The authors thank PLASTFORM d.o.o. for providing technical support and making available the materials and measuring equipment used in this study. This research was funded by the European Union – NextGenerationEU through the Recovery and Resilience Facility under the National Recovery and Resilience Plan 2021–2026, project no. NPOO.C3.2.R3-I1.04.0147 (recEPS). The funding was awarded by the Ministry of Science, Education and Youth of the Republic of Croatia under the "Targeted Scientific Research" Call for Proposals.

REFERENCES

[1] Fond za zaštitu okoliša i energetsku učinkovitost: EnU u zgradarstvu, https://www.fzoeu.hr/hr/enu-u-zgradarstvu/7571, pristupljeno 8.12.2025.

[2] European Parliament and Council: Directive (EU) 2024/1275 on the energy performance of buildings (recast), Official Journal of the European Union, Luxembourg, 2024.

[3] European Parliament and Council: Directive (EU) 2023/1791 on energy efficiency (recast), Official Journal of the European Union, Luxembourg, 2023.

[4] Citadini de Oliveira, C., Catão Martins Vaz, I., Ghisi, E.: Retrofit strategies to improve energy efficiency in buildings: An integrative review, Energy and Buildings, 321 (2024), p. 114624, https://doi.org/10.1016/J.ENBUILD.2024.114624

[5] Ministarstvo prostornoga uređenja, graditeljstva i državne imovine: Energetska obnova zgrada, https://mpgi.gov.hr/o-ministarstvu/djelokrug/energetska-ucinkovitost-u-zgradarstvu/energetska-obnova-zgrada-8321/8321, pristupljeno 10.12.2025.

[6] Michalak, J., Czernik, S., Marcinek, M., Michalowski, B.: Environmental burdens of external thermal insulation systems: Expanded polystyrene vs. mineral wool – Case study from Poland, Sustainability, 12 (2020) 11, https://doi.org/10.3390/su12114532

[7] Michalak, J.: External thermal insulation composite systems (ETICS) from industry and academia perspective, Sustainability, 13 (2021) 24, https://doi.org/10.3390/su132413705

[8] Business Market Insights: Europe ETICS System Materials Market, Market Research Report, 2023.

[9] EAE – European Association for External Thermal Insulation Composite Systems: ETICS on the Way to a Circular Economy, Brussels, 2023.

[10] European Commission: The European Green Deal, https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en, pristupljeno 25.8.2024.

[11] Albrecht, W., Schwitalla, C.: Berichte, Gutachten etc., Fraunhofer IRB, Stuttgart, 2005.

[12] Ugwu, S.C., Obele, C.M.: A mini-review on expanded polystyrene waste recycling and its applications, World Journal of Advanced Engineering Technology and Sciences, 8 (2023) 1, pp. 315–329, https://doi.org/10.30574/wjaets.2023.8.1.0057

[13] Market Growth Reports: Expanded Polystyrene for Packaging Market Size, Share, Growth and Industry Analysis, https://www.marketgrowthreports.com/market-reports/expanded-polystyrene-for-packaging-market-110240, pristupljeno 24.2.2026.

[14] Hrvatski zavod za norme: HRN EN 18092:2025 – Smjernice za dizajn građevnih proizvoda od plastike prilagođen recikliranju – Proizvodi za toplinsku izolaciju od ekspandiranog polistirena (EPS), Zagreb, 2025.

[15] Vukadin, J., Tkalčić, D., Milovanović, B., Banjad Pečur, I.: Characterization of mechanically recycled EPS under compressive and bending loadings.

[16] Europska komisija: Europska strategija za plastiku u kružnom gospodarstvu, Strasbourg, 2018.

[17] European Commission: Commission Notice – The 2022 Annual Union Work Programme for European Standardisation, Brussels, 2022.

[18] European Commission: Delegated Regulation – EU Taxonomy, Annex I, Brussels, 2021.

[19] Industrieverband Hartschaum e.V.: https://www.ivh.de/, pristupljeno 24.2.2026.

[20] Fachverband Wärmedämm-Verbundsysteme e.V.: https://fachverband-wdvs.de/, pristupljeno 24.2.2026.

[21] DIN Media GmbH: DIN 4108-10:2021-11 – Thermal insulation and energy economy in buildings – Part 10: Application-related requirements for thermal insulation materials, Berlin, 2021.

[22] Razvoj inovativne izolacijske ploče s značajnim udjelom reciklata za podno grijanje i hlađenje (recEPS), pristupljeno 11.1.2026.

[23] Albrecht, W., Schwitalla, C.: Rückbau, Recycling und Verwertung von WDVS, Fraunhofer IRB, Stuttgart, 2015.

[24] Deutsches Institut für Normung (DIN): Wärmeschutz und Energie-Einsparung in Gebäuden – Teil 10: Anwendungsbezogene Anforderungen an Wärmedämmstoffe, Berlin, 2015.

[25] Sprengard, C., Treml, S., Holm, A.H.: Technologien und Techniken zur Verbesserung der Energieeffizienz von Gebäuden durch Wärmedämmstoffe, München, 2013.

[26] Europski parlament i Vijeće Europske unije: Uredba (EU) 2019/1021 o postojanim organskim onečišćujućim tvarima, Bruxelles, 2019.

[27] Martin, S., Andreas, M., Monica, D.-S.: Using the CreaSolv® process to recycle polymers from Canadian waste plastics containing brominated flame retardants.

[28] Schöpel, M. et al.: Weiterentwicklung des Umweltzeichens Blauer Engel für Wärmedämmverbundsysteme, Berlin, 2018.

[29] Umweltbundesamt: Wie werden HBCD-haltige Dämmstoffe entsorgt und können sie recycelt werden?, pristupljeno 15.3.2026.

[30] Maul, J., Frushour, B.G., Kontoff, J.R., Eichenauer, H., Ott, K.-H., Schade, C.: Polystyrene and styrene copolymers, Ullmann's Encyclopedia of Industrial Chemistry, Wiley-VCH, 2000.

[31] Schaumaplast Group: Automotive – Lightweight construction with particle foam, https://schaumaplast.com/us/automotive/, pristupljeno 21.12.2025.

[32] The Global EPS Sustainability Alliance: https://globaleps.org/, pristupljeno 21.12.2025.

[33] Maghfouri, M. et al.: Drying shrinkage properties of expanded polystyrene (EPS) lightweight aggregate concrete: A review, Case Studies in Construction Materials, 16 (2022), p. e00919, https://doi.org/10.1016/J.CSCM.2022.E00919

[34] Mohajerani, A., Ashdown, M., Abdihashi, L., Nazem, M.: Expanded polystyrene geofoam in pavement construction, Construction and Building Materials, 157 (2017), pp. 438–448, https://doi.org/10.1016/J.CONBUILDMAT.2017.09.113

[35] Tkalčić, D., Vukadin, J., Milovanović, B., Banjad Pečur, I.: State of the art review in the field of EPS recycling and requirements for the application of EPS in underfloor heating and cooling boards, u: Zbornik radova 29. DIMK, Beograd, 2025, pp. 200–209, https://doi.org/10.46793/29DIMK.200T

[36] González-Betancur, D., Hoyos-Montilla, A.A., Tobón, J.I.: Sustainable hybrid lightweight aggregate concrete using recycled expanded polystyrene, Materials, 17 (2024) 10, https://doi.org/10.3390/ma17102368

[37] Hamidi, N., Galloway, B.: Reprocessing post-consumer expanded polystyrene: Mechanical and thermal properties of lightweight concrete made with post-consumer expanded polystyrene, Journal of Macromolecular Science, Part B, 61 (2022) 6, pp. 811–824, https://doi.org/10.1080/00222348.2022.2113305

[38] Hrvatski zavod za norme: HRN EN ISO 29470:2020 – Toplinsko-izolacijski proizvodi za zgrade – Određivanje prividne gustoće, Zagreb, 2020.

[39] Hrvatski zavod za norme: HRN EN 12667 – Toplinske značajke građevnih materijala i proizvoda – Određivanje toplinskog otpora metodom sa zaštićenom vrućom pločom i tokomjernom metodom, Zagreb, 2002.

[40] Hrvatski zavod za norme: HRN EN ISO 29469:2022 – Toplinsko-izolacijski proizvodi za primjenu u građevinarstvu – Određivanje ponašanja pri tlačnom opterećenju, Zagreb, 2022.

[41] Hrvatski zavod za norme: HRN EN 12089:2013 – Toplinsko-izolacijski proizvodi za graditeljstvo – Određivanje ponašanja pri savijanju, Zagreb, 2013.

[42] Hrvatski zavod za norme: HRN EN 1607:2013 – Toplinsko-izolacijski proizvodi za graditeljstvo – Određivanje vlačne čvrstoće okomito na ravninu ploče, Zagreb, 2013.

[43] Notario, B., Pinto, J., Solorzano, E., De Saja, J.A., Dumon, M., Rodríguez-Pérez, M.A.: Experimental validation of the Knudsen effect in nanocellular polymeric foams, Polymer, 56 (2015), pp. 57–67, https://doi.org/10.1016/j.polymer.2014.10.006

[44] Gibson, L.J., Ashby, M.F.: Cellular Solids: Structure and Properties, Cambridge University Press, Cambridge, 1997.