

Article

Mechanically Recycled Content and Feedstock Source Govern Compressive Energy Absorption in EPS Thermal Insulation

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Abstract

The mechanical performance of expanded polystyrene (EPS) thermal insulation produced with mechanically recycled content has received limited investigation beyond the single point compressive stress at 10% strain (σ_{10}) declared under EN 13163. This study quantifies the cumulative volumetric energy absorption $W(\epsilon)$ and the specific energy absorption $SEA(\epsilon)$ of EPS containing recycled material from two distinct end-of-life sources. Construction waste (S1) and packaging waste (S2) were tested to find whether energy-based metrics reveal source effects masked by σ_{10} . Two nominal density classes, corresponding to the EPS 100 and EPS 150 types, five recycled content levels (0%, 5%, 10%, 25%, 50% by volume), and 235 specimens were tested under EN ISO 29469:2022. A two-way ANOVA framework decomposed the recycling effect into source, content, and interaction components, with Welch's ANOVA, classical ANOVA, and Kruskal–Wallis applied in parallel as robustness checks. Recycled content was the dominant factor across all metrics. The two types behaved differently with respect to source: EPS 100 showed an additive source effect throughout the dose range, while EPS 150 was dominated by a strong source $\times$ content interaction, with the sources equivalent at low doses and S1 substantially outperforming S2 at 50% substitution. A recycled fraction of 5% was statistically equivalent to virgin material in every configuration tested. The findings show that energy-based metrics resolve recycled material source effects that are not detectable on σ_{10} alone, and that the substitution is type-specific rather than universal.

Keywords: thermal insulation; recycled EPS; mechanical recycling; specific energy absorption; circular economy in construction; statistical analysis; ANOVA

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1. Introduction

Expanded polystyrene (EPS) is among the most widely used thermal insulation materials in the European building stock, valued for its low thermal conductivity, low apparent density, and predictable mechanical performance under both short and long-term compressive loading [1–3]. Boards declared under the European product standard used for insulation are declared under the standard EN 13163:2012+A2:2016 [4]. The standard classifies EPS into types by minimum compressive stress at 10% deformation, σ_{10} , with EPS 100 (≥ 100 kPa) and EPS 150 (≥ 150 kPa) representing the load-bearing types commonly specified for thermal insulation applications to compressive loads. The compressive properties governing these declarations are determined under the EN ISO 29469:2022 test protocol [5], evaluated within the 0 to 10% strain envelope.

The compressive behavior of virgin EPS is well characterized in polymer foam literature. The three-regime stress–strain framework (linear-elastic, plateau, densification) and the relative density scaling laws that virtually all later EPS mechanics work builds on are established in [6]. Article [7] links deformation mechanisms (cell-wall bending, buckling, collapse) to the bulk stress–strain response and energy absorption. Krundaeva et al. [8] reported σ_{10} values in the 80 to 150 kPa range for virgin EPS at densities of 20 to 25 kg/m³ under EN ISO 29469 compliant testing, with cell-wall buckling identified as the dominant deformation mechanism in the post-yield regime.

Substantial volumes of EPS originally installed in buildings for thermal insulation between the 1970s and the early 2000s are now reaching the demolition stage, making end-of-life management of EPS a growing concern within the European Union. At the policy level, the European Green Deal has set out the decarbonization and renovation of the building stock as a priority [9], while EU circular economy and sustainable finance instruments increasingly direct construction activity toward material reuse and away from disposal [10]. This shift is reflected in the wider literature on circular economy in the built environment, which has developed methods for quantifying circularity [11] and has mapped the barriers and enablers to its adoption in construction [12]. Within the EPS sector specifically, industry initiatives have begun to document progress toward circularity in production and end-of-life handling [13].

The most direct route to closing the EPS material loop is mechanical recycling, as it does not require the energy and chemical inputs that solvent-based or thermal recovery routes require.

Mechanical recycling represents grinding waste EPS (used and unused) into a heterogeneous mixture of bead clusters, individual beads, and fine particles for reincorporation into new EPS products at controlled substitution levels. However, the mechanical performance of EPS produced with mechanically recycled content has received comparatively very little systematic investigation in the published literature.

The compressive behavior of EPS is characterized in the product standard by a single value, the compressive stress at 10% strain, denoted σ_{10} . Under the procedure of EN ISO 29469, this metric represents the stress the material sustains when compressed by one-tenth of its original thickness. Standards such as EN 13163 utilize σ_{10} to assign products to specific strength types. For instance, EPS 100 and EPS 150 denote boards with a σ_{10} of at least 100 kPa and 150 kPa. While this classification governs how products are declared and specified for load-bearing insulation, σ_{10} samples the stress–strain curve at only a single point. Consequently, two materials sharing the identical σ_{10} value can absorb vastly different amounts of energy on the way to that threshold. Insulation board experiences continuous loading across changing levels of deformation, not at a fixed strain point. Calculating the total energy absorbed during compression, as well as its mass-normalized form, consequently, provides a more complete assessment of mechanical performance than a single declared stress value. This method aligns with standard practices for evaluating polymeric foams in cushioning and structural applications [14]. These materials are typically analyzed using energy absorption diagrams to evaluate performance across the whole loading history for materials selection [15]. A single strain metric like σ_{10} cannot detect structural variations that occur at other points along the curve or increase with deeper deformation. This study measures energy absorption to quantify those underlying differences.

Article [16] tested compressive stress at 10% deformation on mechanically recycled EPS and published the results. The σ_{10} metric records stress at a single strain checkpoint, which is the property declared under the European product standard. However, it does not capture the full mechanical work absorbed during compression.

Authors in article [17] tested virgin EPS for energy absorption and concluded that EPS is well described by the Gibson–Ashby model for the overall density trend, but density alone does not explain all behavior. Whether and how density-based predictions remain valid for EPS containing mechanically recycled material has only recently begun to be addressed.

The present study addresses that question directly. We report the cumulative volumetric energy absorption $W(\epsilon)$ and the specific energy absorption $SEA(\epsilon)$ at two strain checkpoints ($\epsilon = 5\%$ and $\epsilon = 10\%$) for 235 EPS specimens, organized across two nominal density classes (EPS 100 and EPS 150), two recycled material sources (S1 construction; S2 packaging), and five recycled content levels (0%, 5%, 10%, 25%, and 50% by volume). The specimens are drawn from the same set of EPS blocks examined in [16] and were tested under the same EN ISO 29469:2022 protocol, so the design is fully nested within the precursor study, and the two papers can be read together as a single mechanical characterization of the recEPS material set.

The statistical framework decomposes the recycled content effect into a source-attributable component, a source-independent component, and their interaction, separately for each nominal density. Three statistical frameworks (Welch's ANOVA, classical one-way ANOVA, and Kruskal–Wallis) are applied in parallel to ensure that the reported significance conclusions do not depend on any single distributional assumption. The objectives are twofold: first, to establish the recycled content level at which mechanically recycled EPS retains energy absorption performance statistically equivalent to virgin material under the standardized test envelope; and second, to test whether the recycled material source has an effect on energy absorption performance large enough to warrant differentiated specification, given that no such effect was detected on the standardized σ_{10} metric in [16].

2. Materials and Methods

2.1. Materials

EPS composites were manufactured by Plastform d.o.o., Zagreb, Croatia from virgin pre-expanded polystyrene beads blended with mechanically recycled EPS introduced at two substitution levels (5%, 10%, 25%, and 50% by volume), with 0% (virgin EPS) serving as the reference. The recycled fraction consisted of mechanically ground EPS from two end-of-life sources, construction (S1) and packaging (S2), comprising a heterogeneous mixture of bead clusters, individual beads, and fine particles (granules and dust). Two nominal density classes were investigated, with target apparent densities of $\rho_{nominal} = 20 \text{ kg/m}^3$ and $\rho_{nominal} = 25 \text{ kg/m}^3$. These densities are typically associated with EPS board meeting the EPS 100 and EPS 150 strength types. According to EN 13163:2012+A2:2016 [4], these types are defined by a minimum compressive stress at 10% strain of 100 kPa and 150 kPa, respectively. Both types are commonly specified in European thermal insulation applications, including ETICS and underfloor heating insulation panels.

The blends were processed by conventional steam molding into block geometries from which boards were subsequently cut for specimen preparation. Three boards from each block's diagonal were tested to enable the assessment of variation within the block.

2.2. Specimen Preparation and Conditioning

Cubic specimens of nominal dimensions $100 \times 100 \times 50 \text{ mm}$ were cut from the produced boards in accordance with the geometry and tolerance requirements of EN ISO 29469:2022 [5]. From each board, five specimens were prepared, providing a sampling

structure (block–board–specimen) that enables the between-block separation, between-board, and within-board variability sources.

Prior to mechanical testing, all specimens were climate-controlled in a laboratory at 23 ± 2 °C and $50 \pm 5\%$ relative humidity for a minimum of 7 days in accordance with EN ISO 291:2008 [18].

Specimen-by-specimen identification was preserved through testing using the alpha-numeric coding scheme Block–NominalDensity–RecycledContent%–Board–CS# (e.g., S1–20–25–V3–CS3). Letter “R” in R-20-0% and R-25-0% labels reference material with 0% recycled content (100% virgin EPS).

The complete specimen inventory comprised 267 specimens distributed across the (nominal density $\times$ recycled content) grid as summarized in Table 1.

Table 1. Distribution of tested specimens across nominal density and recycled content groups.

Series	Recycled EPS Content [%]	Nominal Density [kg/m ³]	Type of Recycled EPS
R-20-0%	0	20	Construction (S1)
S1-20-5%	5		
S1-20-10%	10		
S1-20-25%	25		
S1-20-50%	50		
R-25-0%	0	25	Construction (S1)
S1-25-5%	5		
S1-25-10%	10		
S1-25-25%	25		
S1-25-50%	50		
S2-20-5%	5	20	Packaging (S2)
S2-20-10%	10		
S2-20-25%	25		
S2-20-50%	50		
S2-25-5%	5	25	Packaging (S2)
S2-25-10%	10		
S2-25-25%	25		
S2-25-50%	50		

2.3. Apparent Density Determination

The apparent density of each board was determined according to EN ISO 845:2009 [19]. Board dimensions were measured at three positions per axis using a Stiro-Lab XYZ.320 measuring table (Stirolab, Logatec, Slovenia) and a Suki 0–150 mm caliper (suki.international GmbH, Landscheid, Germany). Mass was recorded on a digital balance, Kern PCD10KO, a non-automatic electronic precision balance scale. The reported density value for each board was assigned to all specimens cut from the board, on the assumption that within-board density variation is small relative to between-board variation.

2.4. Compressive Testing

Compressive testing was performed in accordance with EN ISO 29469:2022 [5]. Tests were carried out on 267 specimens. Compressive load was applied along the specimen thickness direction (50 mm) at a constant crosshead displacement rate corresponding to the EN ISO 29469 specification. Force and crosshead displacement were continuously recorded. Each test was continued until a compressive strain of 10% was reached, in accordance with the strain envelope required for the determination of the compressive stress at

10% deformation, σ_{10} , the standardized property used for the EN 13163 EPS type declaration [4]. Following test termination, raw force-displacement data were exported and converted to compressive stress and strain using the nominal specimen cross-section area (10,000 mm²) and initial specimen thickness (50 mm), respectively.

2.5. Quality Control and Specimen Exclusion

Stress–strain curves were digitized from laboratory reports using Python [20], and libraries Numpy [21], Pillow [22], pdf2image [23] and openpyxl [24]. All recorded stress–strain curves were inspected visually as a quality-control step prior to statistical analysis. Specimens were excluded from the analysis when the curve showed evidence of test-protocol anomalies, including (i) edge crushing or asymmetric loading, manifested as a localized stress drop or shape discontinuity in the post-yield region; (ii) extensometer or platen slippage, manifested as a discontinuity in the strain record. Exclusion decisions were made strictly based on physical or test-protocol evidence and not on the magnitude of derived properties. A total of 32 specimens were excluded under these criteria, leaving 235 specimens for analysis.

2.6. Energy Absorption Metrics

The compressive energy absorbed per unit volume up to a strain ε , denoted $W(\varepsilon)$ and expressed in kJ/m³, was computed from each specimen's stress–strain record by trapezoidal numerical integration:

$$W(\varepsilon) = \int_0^{\varepsilon} \sigma(\varepsilon') d\varepsilon' \quad (1)$$

Integration was performed on the raw, unsmoothed force-displacement record to preserve fidelity in the immediate post-yield region where energy contributions are most sensitive to local curvature. The endpoint at the target strain included a linear interpolation between adjacent data points to avoid truncation errors. The corresponding specific energy absorption, denoted $SEA(\varepsilon)$ and expressed in J/kg, was obtained by normalizing $W(\varepsilon)$ to the apparent density ρ of the specimen:

$$SEA(\varepsilon) = \frac{W(\varepsilon)}{\rho} \quad (2)$$

While W indicates total energy per volume, SEA indicates material absorption per mass, as this analysis consists of materials with different densities. Each approach isolates whether recycling changes intrinsic material quality or just density.

Both metrics were evaluated at two strain levels, $\varepsilon = 5\%$ and 10% selected to cover the full deformation envelope relevant to long-term service of EPS thermal insulation in load-bearing building applications. The below 5% levels capture the elastic and early post-yield response under typical permanent-load conditions in ETICS and underfloor heating systems [25], while the 10% level corresponds to the limiting strain used for the EN 13163 [4] EPS type declaration.

2.7. Statistical Analysis

The analytical framework was chosen to enable formal hypothesis testing of two independent factors, recycled material source (S1, S2) and recycled content (5%, 10%, 25%, 50%), on the energy absorption metrics. Because the dataset has the structure of a designed factorial experiment with multiple categorical groups rather than a single continuous response, analysis of variance (ANOVA) methods were selected as the appropriate tool. ANOVA tests the null hypothesis that two or more group means are equal by comparing the spread between group means to the spread within each group. If the spread between groups is much larger than within-group variability, the null hypothesis is rejected, and

the groups are deemed to differ [26]. The reported tests share a common logical foundation, differing only in their underlying assumptions regarding the data.

A two-way ANOVA was the primary test for the source effect. This procedure simultaneously estimates three quantities: (i) whether the recycled material source significantly affects the response on average (the source main effect), (ii) whether the recycled content level significantly affects the response on average (the recycled content main effect), and (iii) whether the effect of recycled content depends on which source is used (the source $\times$ recycled content interaction). The interaction term is the most informative of the three: a significant interaction means that S1 and S2 have different dose-response trajectories, while a non-significant interaction with a significant source main effect means S1 and S2 differ by a constant offset across all recycled levels. The first scenario implies that source choice depends on the substitution level, while the second implies that source choice is a one-time decision applicable across all doses.

The two-way ANOVA was run on the recycled-only subset of data (5%, 10%, 25%, 50%), with virgin specimens (0%) reserved as a shared reference baseline. Type II sums of squares were used, which compute each main effect after accounting for the other main effect but ignoring the interaction; this is the recommended choice for designs in which group sizes are not perfectly balanced [27], as is the case here, following the documented specimen exclusions in Section 2.5. Effect size was quantified using partial eta-squared (η_p^2) that measures the proportion of variance attributable to a given factor while controlling for the others. Cohen's benchmarks [28], small (≥ 0.01), medium (≥ 0.06), and large (≥ 0.14), were used to interpret the magnitude of each effect, complementing the p -value with practical significance.

Classical ANOVA rests on three key assumptions about the data: (i) independent measurements, (ii) normal distribution within each group, and (iii) equal variance across groups. When both hold, the procedure produces accurate p -values. When they fail, the calculated p -values can be misleading.

To verify these assumptions, two diagnostic tests were applied to every ($\rho_n \times$ metric $\times$ strain) combination, namely the Shapiro–Wilk test and Levene's test. The Shapiro–Wilk test [29] examines whether the data in each group are consistent with a normal distribution. A p -value below 0.05 indicates a departure from normality. Levene's test with median centering [30] examines whether variances are equal across groups. A p -value below 0.05 indicates heterogeneous variances. It has to be said here that across the metrics tested in this study, Shapiro–Wilk detected mild departures from normality in some groups (3 of 5 groups in the EPS 100 modulus analysis), and Levene's test detected variance heterogeneity in others ($p = 0.009$ for modulus across recycled levels). Since these violations are not unusual for material testing data with moderate sample sizes, we used additional tests in parallel as a robustness check.

Two additional frameworks were applied to every analysis as confirmatory checks. The role of these tests is to determine whether the primary ANOVA conclusions are robust against the specific violations detected by re-evaluating the same hypotheses under different assumption sets.

Welch's ANOVA [31] is a heteroscedasticity-robust variant of the classical procedure. It modifies the F -statistic calculation and adjusts the degrees of freedom to account for unequal group variances, providing valid p -values even when the homoscedasticity assumption is violated. It is the recommended primary test in many modern statistics references when Levene's test flags variance differences. In this study, Welch's ANOVA was applied as a within-source dose–response analysis on each individual recycled material source against the virgin baseline.

Kruskal–Wallis [32] is a non-parametric alternative that makes no distributional assumption. Instead of working with the actual measured values, it ranks all observations

from smallest to largest and tests whether the ranks are distributed evenly across groups. Because rank-based statistics are insensitive to outliers and non-normal shapes, Kruskal–Wallis provides a check that does not depend on the normality assumption at all. It is less powerful than ANOVA when the data happens to be normal, but it serves as a sensitivity check: if a conclusion holds under both parametric and non-parametric analysis, the conclusion is independent of the distributional model.

For every combination of metric, strain level, and density we examined, all three statistical tests, classical ANOVA, Welch’s ANOVA, and Kruskal–Wallis, have reached the same conclusion about whether the differences were statistically significant. We used a significance threshold of 0.05, meaning a result was treated as significant only if there was less than a 5% probability of observing it by chance alone if no real effect existed. Because the three tests agreed at this threshold despite resting on different assumptions, we can be confident that the findings are robust and not an artifact of the specific assumption violations we detected.

ANOVA tests whether some group means differ, but does not identify which groups differ. With five groups (virgin plus four recycled levels) per source, ten pairwise comparisons are possible. Running these ten comparisons as independent t -tests at $\alpha = 0.05$ would inflate the family-wise error rate to roughly 40%, meaning a 40% chance of at least one false-positive by chance alone. Post hoc procedures correct for this by adjusting the significance threshold or recalculating it for each comparison.

Three post hoc procedures were applied in parallel, each suited to a different situation. The Games–Howell test [33] was the primary procedure and was used for all pairwise comparisons between groups. It was chosen because it handles two problems at once: groups with unequal variances and groups of unequal size. Unlike standard post hoc tests, it does not assume that all groups share the same variance (an assumption our data violated). Dunn’s test [34] with the Holm correction [35] served as the rank-based counterpart; it is the post hoc test that naturally follows the Kruskal–Wallis analysis, since both work on ranked rather than raw values.

Finally, Welch’s t -test [36] was used for the direct two-group comparisons, specifically, S1 versus S2 at each individual recycled content level. Welch’s t -test gives reliable results when the two groups being compared have unequal variances, which makes it the appropriate choice for these head-to-head contrasts.

For each statistically significant pairwise contrast, the magnitude of the difference was quantified using Cohen’s d [28]. Cohen’s d expresses the difference between two group means in units of the pooled standard deviation within the group. Cohen’s d distinguishes a statistically detectable difference from a practically meaningful one: a small Cohen’s d ($|d| \geq 0.2$) indicates a barely noticeable effect; medium (≥ 0.5) a meaningful one; large (≥ 0.8) a substantial one.

The three tests were run in parallel as a robustness check, as each test rests on different assumptions. Agreement across all tests indicates that a conclusion does not depend on which method was chosen.

All statistical computation was performed in Python 3.12.12 [20] using NumPy [21], pandas [37], SciPy [38], scikit-posthoc [39], statsmodels [40], and Matplotlib [41] libraries.

3. Results

3.1. Compressive Stress–Strain Response

Figure 1 shows the representative compressive stress–strain response of all EPS specimen groups, separated by nominal density class. Solid lines indicate the median curve. Dashed red reference line indicates the EN 13163 EPS 100 threshold ($\sigma_{10} = 100$ kPa) and EPS 150 threshold ($\sigma_{10} = 150$ kPa).

The two recycled material sources investigated in this study are recycled construction EPS material (S1) and recycled packaging EPS material (S2). Quantitative differences between sources are addressed in Section 3.4. All curves exhibit the characteristic three-regime behavior of closed-cell rigid polymer foams and an initial quasi-linear elastic region extending to approximately 1.5–2.5% strain. A yield knee is marking the onset of progressive cell-wall buckling, and a developing collapse plateau that continues throughout the remainder of the tested envelope ($\varepsilon \leq 10\%$) without entering densification.

The 5% recycled-content groups were visually indistinguishable from the virgin reference in all four (sources $\times$ type) combinations. Mixtures with higher recycled content are separated progressively from virgin, with the rate of separation differing between sources and types. The 25% and 50% groups exhibited progressively reduced stress at any given strain, with the magnitude of the reduction depending on both the recycled material source and the nominal density class. At $\varepsilon = 10\%$, all virgin and most recycled groups in the $\rho_{nominal} = 20 \text{ kg/m}^3$ class exceed the 100 kPa threshold required for the EPS 100 declaration under EN 13163 [4]; quantitative type compliance is reported in Section 3.4.

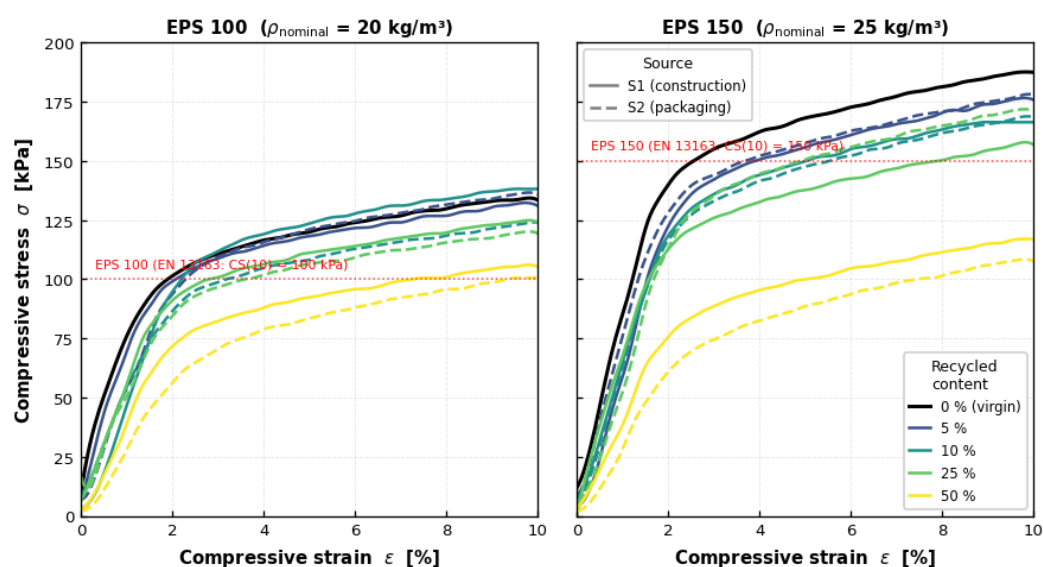


Figure 1. Compressive stress–strain response.

3.2. Energy Absorption Across the Tested Strain Envelope

The cumulative compressive energy absorbed per unit volume, $W(\varepsilon)$, and the corresponding specific energy absorption, $SEA(\varepsilon) = W(\varepsilon)/\rho$, were computed for every specimen at two strain levels (5% and 10%) following the procedure described in Section 2.6.

Figure 2 shows cumulative compressive energy absorbed per unit volume, $W(\varepsilon)$, as a function of strain for each source $\times$ recycled content combination. Solid lines represent group means, while shaded bands represent 95% confidence intervals, stratified by nominal density class, with separate trajectories for construction (S1) and packaging (S2) recycled materials. Trajectories for S1 and S2 are visually indistinguishable across all groups at strains below approximately 1%, separate progressively over the 1–5% range, and reach maximum vertical separation at 10% strain. The relative ordering of the trajectories at each density class differs between the two density panels, reflecting source-dependent dose-response patterns examined formally in Sections 3.3 and 3.4.

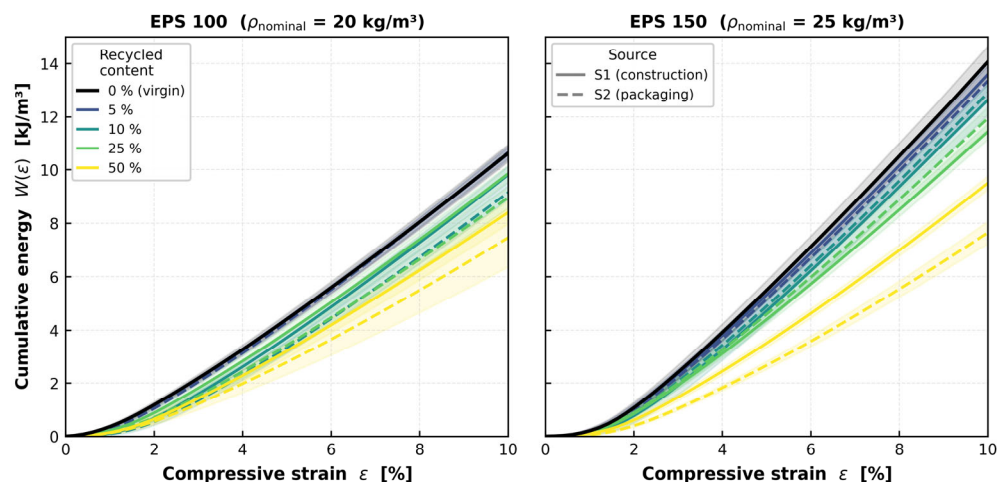


Figure 2. Cumulative compressive energy absorbed per unit volume.

Direct source comparisons at $\varepsilon = 10\%$ strain are shown in Figure 3 (EPS 100) and Figure 4 (EPS 150). Separation between S1 and S2 is most pronounced at 10% and 25% recycled content for EPS 100, and at 50% recycled content for EPS 150.

Figure 3 shows the energy absorption comparison between recycled material sources at the EPS 100 type. Top row: cumulative volumetric energy absorbed at 10% strain (W_{10}). Bottom row: specific energy absorption at 10% strain (SEA_{10}). Each panel shows virgin (V, gray), recycled material from construction source (S1, blue), and packaging source (S2, red) at one recycled content level. Brackets above S1 and S2 pairs indicate Welch t -test outcomes (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; n.s.: not significant).

Figure 4 shows the energy absorption comparison between recycled material sources at the EPS 150 type. Layout, plotting conventions, and statistical annotations are identical to Figure 3. Tables 2 and 3 show σ_{10} , W_{10} , and SEA_{10} metrics for source $\times$ recycled content for $\rho_{nominal} = 20 \text{ kg/m}^3$ and $\rho_{nominal} = 25 \text{ kg/m}^3$.

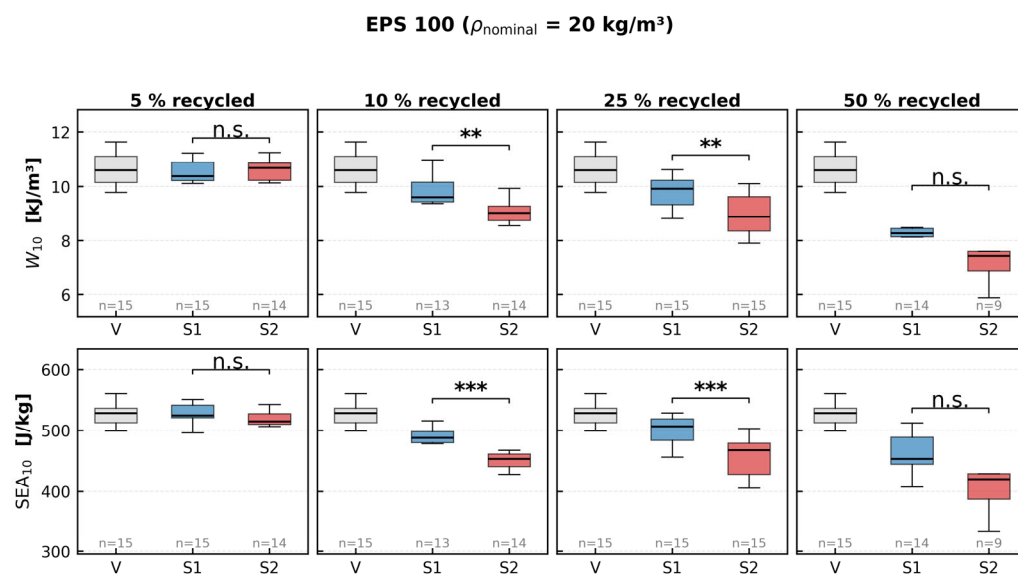


Figure 3. Comparison of energy-absorption performance between recycled material sources at the EPS 100 type ($\rho_{nominal} = 20 \text{ kg/m}^3$). (** $p < 0.01$; *** $p < 0.001$; n.s.: not significant).

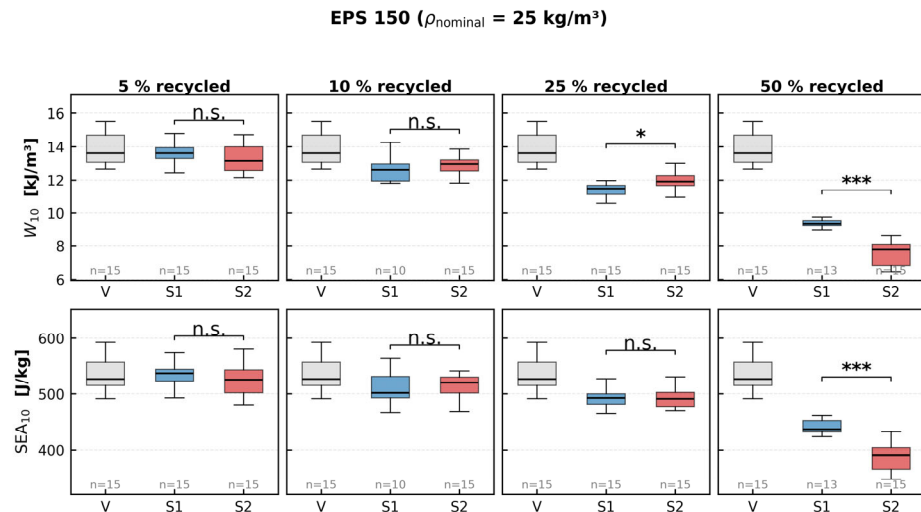


Figure 4. Comparison of energy absorption performance between recycled material sources at the EPS 150 type ($\rho_{\text{nominal}} = 25 \text{ kg/m}^3$). (* $p < 0.05$; *** $p < 0.001$; n.s.: not significant).

Table 2. Descriptive statistics by cell for $\rho_{\text{nominal}} = 20 \text{ kg/m}^3$.

Source	Recycled Content [%]	n	σ_{10} [kPa]	W_{10} [kJ/m³]	SEA_{10} [J/kg]
Virgin	0	15	130.2 ± 4.1	10.6 ± 0.6	526.1 ± 18.5
S1	5	15	130.2 ± 3.9	10.6 ± 0.4	529.5 ± 19.1
S1	10	13	128.6 ± 4.7	9.8 ± 0.5	492.1 ± 15.6
S1	25	14	124.2 ± 3.6	9.8 ± 0.5	502.4 ± 22.0
S1	50	11	109.8 ± 6.3	8.4 ± 0.6	468 ± 29.8
S2	5	14	133.6 ± 4.0	10.6 ± 0.4	518.5 ± 11.2
S2	10	13	123 ± 4.5	9.2 ± 0.4	457.4 ± 23.5
S2	25	15	117.2 ± 4.9	9.0 ± 0.7	458.1 ± 31.6
S2	50	8	100.3 ± 15.2	7.5 ± 1.3	418.4 ± 68

Table 3. Descriptive statistics by cell for $\rho_{\text{nominal}} = 25 \text{ kg/m}^3$.

Source	Recycled Content [%]	n	σ_{10} [kPa]	W_{10} [kJ/m³]	SEA_{10} [J/kg]
Virgin	0	13	180.3 ± 8.1	14.07 ± 1.0	539.9 ± 33.5
S1	5	15	174.4 ± 5.5	13.6 ± 0.6	534.3 ± 19.5
S1	10	10	165.9 ± 5.4	12.6 ± 0.8	508.7 ± 30.5
S1	25	15	149.0 ± 5.2	11.4 ± 0.5	494.8 ± 22.8
S1	50	12	128.4 ± 5	9.5 ± 0.4	447.9 ± 22.2
S2	5	13	173.1 ± 7.2	13.3 ± 0.9	527 ± 31.6
S2	10	15	169.5 ± 5.2	12.9 ± 0.6	514.3 ± 20.8
S2	25	15	155.4 ± 7.4	11.9 ± 0.8	486.9 ± 28.8
S2	50	12	108.2 ± 8.8	7.6 ± 0.7	389.3 ± 23.4

3.3. Two-Way Decomposition of the Recycling Effect

The combination of two recycled material sources (S1, S2), four recycled content levels (5%, 10%, 25%, 50%), and two density classes can be separated by the effect of recycled content into three parts: the share that depends on which source the recycled material came from, the share that does not, and any interaction between source and content. A separate two-way ANOVA was run for each energy metric at each strain level and each

density class. Virgin specimens were kept as a reference. The full results are reported in Tables 4 and 5.

In every case, recycled content was the dominant factor, with η_p^2 values between 0.500 and 0.922, all significant at $p < 0.001$. The role of the source factor and its interaction with recycled content behaved differently between the two nominal densities.

For EPS 100, the source effect was significant on every metric, with η_p^2 between 0.117 and 0.268. The source $\times$ recycled interaction was small to moderate and not consistent across metrics: it reached statistical significance on σ_{10} ($\eta_p^2 = 0.153$, $p = 0.001$) and on W_{10} ($\eta_p^2 = 0.103$, $p = 0.015$) but remained non-significant on SEA_{10} and on both metrics evaluated at 5% strain.

For EPS 150, the pattern was reversed. The source effect was significant on every metric but small in magnitude, with η_p^2 between 0.026 and 0.100. The source $\times$ recycled content interaction was a secondary effect; it was significant on every metric ($p \leq 0.002$) and reached large effect sizes, with η_p^2 between 0.129 and 0.407. The two strongest interaction terms were observed on the compressive stress at 10% strain (σ_{10} , $\eta_p^2 = 0.407$, $p \leq 0.0001$) and on the volumetric energy absorption at 10% strain ($\eta_p^2 = 0.323$ for W_{10}).

Table 4. Two-way ANOVA results for $\rho_{nominal} = 20 \text{ kg/m}^3$.

Metric	Recycled Content [%]	F	p	Significance	η_p^2	Effect Size
σ_{10}	Source	12.62	0.0006	***	0.117	Medium
σ_{10}	Recycled	76.79	<0.0001	***	0.708	Large
σ_{10}	Source $\times$ Recycled	5.73	0.0012	**	0.153	Large
W_{10}	Source	21.33	0.0001	***	0.183	Large
W_{10}	Recycled	68.22	<0.0001	***	0.683	Large
W_{10}	Source $\times$ Recycled	3.64	0.016	*	0.103	Medium
SEA_{10}	Source	34.83	<0.0001	***	0.268	Large
SEA_{10}	Recycled	31.70	<0.0001	***	0.500	Large
SEA_{10}	Source $\times$ Recycled	2.33	0.0796	n.s.	0.068	Medium

(* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; n.s.: not significant).

Table 5. Two-way ANOVA results for $\rho_{nominal} = 25 \text{ kg/m}^3$.

Metric	Recycled Content [%]	F	p	Significance	η_p^2	Effect Size
σ_{10}	Source	3.45	0.066	n.s.	0.034	Small
σ_{10}	Recycled	390.79	<0.0001	***	0.922	Large
σ_{10}	Source $\times$ Recycled	22.65	<0.0001	***	0.407	Large
W_{10}	Source	4.43	0.0379	*	0.043	Small
W_{10}	Recycled	261.74	<0.0001	***	0.888	Large
W_{10}	Source $\times$ Recycled	15.78	<0.0001	***	0.323	Large
SEA_{10}	Source	11.01	0.0013	***	0.100	Medium
SEA_{10}	Recycled	96.71	<0.0001	***	0.746	Large
SEA_{10}	Source $\times$ Recycled	7.80	<0.0001	***	0.191	Large

(* $p < 0.05$; *** $p < 0.001$; n.s.: not significant).

3.4. Source-Specific Effects

The dose–response relationship was tested separately for S1 and S2 within each density class, using Welch’s ANOVA across the five content levels, with classical one-way ANOVA and Kruskal–Wallis as parallel checks. All 20 combinations (two density classes, two sources, five metrics) were significant under all three frameworks, with large effect

sizes (η^2 from 0.540 to 0.733 in EPS 100 and from 0.475 to 0.924 in EPS 150). Full results are given in Appendix A Table A1.

Pairwise S1 vs. S2 contrasts at each content level were computed with Welch's *t*-test (Tables A2 and A3). At 5% recycled content, the sources did not differ significantly on any metric in either density class, except for σ_{10} in EPS 100, where S2 exceeded S1 by a small margin ($d = -0.86$, $p = 0.029$).

In EPS 100, S1 exceeded S2 at 10% and 25% on every metric (d from +1.20 to +1.73). At 50%, the difference favored S1 but was not significant on any metric (p between 0.09 and 0.13).

In EPS 150, the sources did not differ at 5% or 10%. At 25%, S2 exceeded S1 on σ_{10} ($d = -1.01$, $p = 0.011$) and W_{10} ($d = -0.78$, $p = 0.042$), with no difference on SEA_{10} . At 50%, S1 exceeded S2 on all three metrics by a wide margin ($d = +2.82$ for σ_{10} , +3.43 for W_{10} , +2.56 for SEA_{10} ; $p < 0.001$ in each case).

4. Discussion

4.1. Practical Implications

The clearest practical result concerns the lowest substitution level. At 5% recycled content, none of the energy metrics showed a statistically significant difference from virgin EPS. This is held for both recycled material sources, at both nominal densities, which makes 5% a substitutional level that can be adopted with no measurable penalty to energy absorption.

4.2. Energy Absorption Decreases with Recycled Content, and the Effect Grows with Strain

As the proportion of recycled expanded polystyrene increased, compressive energy absorption dropped steadily, and this trend was far stronger than any other effect we measured. In the per source analysis, recycled content by itself explained between roughly 47% to 92% of the variation in energy metrics. The two-way models agreed: the η_p^2 for the recycled content never fell below 0.500. Everything else the data shows about recycled material source or nominal density is a refinement on top of this one dominant pattern. Mechanical reprocessing lowers the energy absorption capacity of EPS, and the more reprocessed material a board contains, the larger the loss. This is consistent with earlier work showing that repeated processing of polystyrene foam gradually breaks down its cellular structure.

Loss behavior with strain is more subtle, and there are two reasonable ways of measuring it, which led to opposite-sounding conclusions. Measured as a statistical effect on cumulative absorbed energy, the influence of recycled content gets stronger as the specimen is compressed further. The η_p^2 rose from 0.64 at 5% strain to 0.69 at 10% for the EPS 100, and more sharply for EPS 150, from 0.78 to 0.89. By this measure, recycled content matters more as the foam is pushed into the plateau region of the stress-strain curve, where most of the energy is absorbed and where weaknesses in the recycled material have the most room to show.

Measured in a different way, the situation reverses. When the loss is expressed in relative terms, the percentage of energy lost compared with the virgin baseline, the gap shrinks at higher strain. At the most heavily recycled EPS 100 condition, cumulative energy was about 37% below virgin at 5% strain, but only 30% below it at 10%. Across the plateau, even degraded foam keeps absorbing energy, so the virgin and recycled curves partly close the gap in cumulative terms, even as the share of variance attributable to recycled content keeps rising.

4.3. Recycled Material Source Modulates Performance in a Type-Dependent Manner

The source of the recycled material resulted in different behaviors between the two density classes. For EPS 100, the source had a steady, across-the-board influence. Recycled construction material (S1) outperformed packaging-derived material (S2) throughout the dose range. The main effect was statistically significant, with η_p^2 between 0.12 and 0.27, and the interaction between source and content was comparatively small, reaching significance only on σ_{10} and W_{10} ($\eta_p^2 \leq 0.153$). In effect, the two recycled material sources declined in parallel, with S1 keeping a consistent lead over S2. The one reversal at low dose in EPS 100, where S2 slightly exceeded S1 on σ_{10} at 5%, was confined to a single metric and was not reflected in the energy measures at the same dose, so it does not indicate a genuine performance advantage for the packaging source.

For EPS 150, the pattern flipped. The averaged source effect became small (η_p^2 between 0.026 and 0.100), while the interaction became large and highly significant (η_p^2 between 0.129 and 0.407). The small main effect at EPS 150 does not mean the source barely matters at that type, but the average difference changes sign across the dose range rather than focusing in one consistent direction.

At EPS 100, S1 was significantly better than S2 at the doses of 10% and 25%, with large, standardized differences, Cohen's d of roughly 1.4 to 1.7 on W_{10} and SEA_{10} . S1 also performed better at 50% but did not reach significance. At EPS 150, the two recycled material sources were statistically indistinguishable at 5% and 10% on every metric. At 25%, the ranking reversed, with S2 significantly exceeding S1 on σ_{10} and W_{10} before inverting again at 50%, where the advantage of S1 over S2 was very large, with d between 2.6 and 3.4. Note that the dose grid used does not contain a point between 25 and 50%. Since S1 and S2 are separated largely at 50%, the dose-response trajectories of the two sources must cross each other somewhere within a 25 to 50% interval, but the present sampling cannot say whether the divergence is gradual through this window, or whether it appears sharply at some specific threshold, and cannot be resolved from these data.

4.4. Degradation Exceeds What Density Loss Alone Predicts

The decline in mechanical performance cannot be attributed solely to the reduction in material density. While reprocessing lowered the board's apparent density, the corresponding drop in energy absorption did not scale proportionally with this mass loss. Had the degradation been a simple consequence of material dilution, the relative reduction in compressive stress would have directly matched the relative decrease in density at a near 1:1 ratio. Instead, at the substitution levels where the material was substantially degraded (25% and 50%), the ratio of strength loss to density loss stayed above one in every degraded condition, ranging from about 1.4 to 3.2. The remaining material is not just less dense; each unit of mass is mechanically weaker, which points to damaged cell walls and poorer fusion between beads rather than density change alone. The source effect sits directly on this mechanism. At the same density loss, the packaging-derived recycled material gave up considerably more strength than the construction-derived one. At 25% recycled content in EPS 100, for example, both sources lost close to 3% of their density, yet S2 lost about 10% of its compressive stress while S1 lost only 5%.

The denser EPS 150 matrix seems to cushion the weaknesses of the recycled material up to moderate loading, so the two sources stay equivalent until the structure can no longer absorb the burden and the weaker recycled material fails between 25% and 50%. The lighter EPS 100 matrix has less reserve, so the same degradation shows up earlier, at the intermediate doses.

The fact that strength falls faster than density suggests the recycled material weakens the cellular structure itself rather than simply lowering the amount of material present. A likely reason is damage to cell walls and poorer fusion between beads during repro-

cessing, but this study did not include microstructural analysis, so the mechanism cannot be confirmed here.

4.5. Why the Two Sources Behave Differently

This data did not establish why the two sources diverge, but several differences between construction and packaging EPS waste could contribute. These include, but are not limited to, surface contamination from its prior use, differences in additive content, age, weathering history, or other source-specific factors of the material before the reprocessing process. Any of these could lower the quality of the recycled beads and the strength of the bonds they form. Identifying which factor dominates would require compositional and thermal characterization of the two recycled material sources, which were outside the scope of this study.

4.6. Limitations

Several constraints on the present results should be stated explicitly so that the conclusions are read in the right context.

Testing was limited to 10% strain, as required by EN ISO 29469 for declared grade classification. This range covers the short-term compressive behavior relevant to load-bearing thermal insulation under EN 13163, but it does not reach densification. Therefore, the full energy absorption capacity cannot be determined from the present dataset, and the densification strain cannot be identified. The material response above 10% strain lies outside the scope of this study and should not be extrapolated from the results reported here.

The dose grid in this study sampled recycled content at five discrete levels (0%, 5%, 10%, 25%, and 50%), leaving a 25% gap with no measurements between the 25% and 50% conditions. Whether the source impact develops gradually as recycled content rises from 25% toward 50%, or whether it appears abruptly at some specific threshold, cannot be determined from these data.

The structural explanation offered for the loss of energy absorption rests on the mechanical data alone. No microscopic or tomographic examination of the cell structure was carried out, so the roles of cell-wall damage and incomplete bead fusion remain unconfirmed. Consequently, future research utilizing SEM is highly recommended to visualize microstructural mechanics and isolate the failure modes.

Finally, the boundary of statistical equivalence with virgin reference falls within an unresolved interval. For the EPS 100 type with S2 recycled material, performance is equivalent to virgin at 5% but no longer at 10%, with no specimens tested between these levels; similar gaps exist for other (source $\times$ type) combinations. The exact location of the equivalence boundary cannot be pinpointed from the data we have.

5. Conclusions

This study measured the compressive energy absorption of EPS thermal insulation containing mechanically recycled materials from two end-of-life sources, construction waste (S1) and packaging waste (S2), at recycled contents from 0% to 50% by volume. A total of 238 specimens were tested under EN ISO 29469 across two nominal density classes corresponding to the EPS 100 and EPS 150 types. Cumulative volumetric energy absorption and specific energy absorption were evaluated at 5% and 10% strain and analyzed with a two-way framework that separated the effects of recycled content, recycled material source, and their interaction. Recycled content dominated the response. It accounted for between 48% and 92% of the variance in energy metrics, and its effect grew as the specimens were compressed further into the plateau region, with the η_p^2 for cumulative energy rising from 0.632 to 0.683 in EPS 100 and from 0.783 to 0.888 in EPS 150 between

the two strain checkpoints. At 5% recycled content, no metric differed significantly from virgin material in either type or for either source. This level can therefore be treated as a substitution point at which energy absorption is not measurably reduced.

The recycled material source affected performance; the way it did so depended on the EPS type. In EPS 100, the source acted as a consistent offset across the dose range, with S1 ahead of S2 at 10% and 25% recycled content by effect sizes between 1.4 and 1.7. In EPS 150, the source effect was concentrated at the top of the dose range: two sources were indistinguishable at 5% and 10%. At 50%, S1 exceeded S2 by a wide margin, with effect sizes between 2.6 and 3.4 at 50% substitution. Construction source material retained 83% of the virgin specific energy absorption in EPS 150 against 72% for packaging source material. When the energy absorbed across the whole loading path is measured instead, the source difference becomes detectable, and it is both strain-dependent and type-dependent. Therefore, energy absorption resolves a dimension of recycled EPS behavior that the declared strength property leaves undescribed.

The results support a substitution guideline that is specific to the EPS type rather than uniform. A 5% recycled fraction can be used without measurable penalty. Above that level, the tolerable content and the choice of feedstock depend on the type: EPS 150 accommodated recycled material without a source penalty further into the dose range, while EPS 100 began to separate the two feedstocks at 10%. Where a high recycled fraction is required, construction source recycled material is the better choice on energy absorption grounds. The strength loss also exceeded the density loss in every substantially degraded condition, by factors between 1.4 and 3.2, so the reduction in performance cannot be treated as simple dilution and should not be predicted from density alone.

Several limitations bound these conclusions. The mechanism behind the degradation was inferred from the mechanical data. Damage to cell walls and poorer fusion between beads is a plausible explanation for strength falling faster than density, but no microstructural analysis was performed, and the mechanism remains unconfirmed. The reason two recycled material sources behave differently cannot be identified from these data. The dose grid also contains no point between 25% and 50% recycled content, and the source ranking changes across that interval in EPS 150; the location at which the two sources diverge cannot be resolved. Testing was limited to 10% Straub, as required for declared classification, so the behavior of recycled content EPS beyond that strain is not addressed here.

These limitations point to the work that would extend the findings. Microstructural and compositional characterization of the recycled material would test the inferred mechanism directly and identify which differences between construction and packaging waste drive the observed source effect. Sampling intermediate recycled contents between 25% and 50% would locate the range at which the sources diverge. Extending the measurement beyond 10% strain would show whether the source effects reported here persist, grow, or disappear in the densification regime, which is the range relevant to impact and overload rather than to declared classification.

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Appendix A

This appendix supports the analyses reported in Sections 3.3 and 3.4 with the statistical details underlying the summary claims in the main text. Table A1 reports the results of dose–response analysis per source across three statistical frameworks—Welch’s ANOVA, classical one-way ANOVA, and Kruskal–Wallis—all run in parallel as a robustness check against the assumption violations detected during preliminary diagnostics. The three frameworks reached identical significance conclusions in every one of the 20 combinations tested, supporting the inferential robustness of the dose–response finding. Table A2 and Table A3 report the direct S1 vs. S2 pairwise contrasts (Welch *t*-test, with Cohen’s *d* effect sizes) at each recycled content level for the three headline metrics (σ_{10} , W_{10} , SEA_{10}), each for one density class. These contrasts substantiate the source-comparison claims in Section 3.4 and the discussion, including the dose-by-dose ranking patterns at each type.

Table A1. Dose–response analysis per source across three statistical frameworks.

Source × Nominal Density	Metric	Welch <i>p</i>	ANOVA <i>p</i>	KW <i>p</i>	η^2	Effect Size
S1-20	σ_{10}	<0.0001	<0.0001	<0.0001	0.733	Large
S1-20	W_5	<0.0001	<0.0001	<0.0001	0.644	Large
S1-20	W_{10}	<0.0001	<0.0001	<0.0001	0.681	Large
S1-20	SEA_5	<0.0001	<0.0001	<0.0001	0.560	Large
S1-20	SEA_{10}	<0.0001	<0.0001	<0.0001	0.540	Large
S2-20	σ_{10}	<0.0001	<0.0001	<0.0001	0.725	Large
S2-20	W_5	<0.0001	<0.0001	<0.0001	0.704	Large
S2-20	W_{10}	<0.0001	<0.0001	<0.0001	0.728	Large
S2-20	SEA_5	<0.0001	<0.0001	<0.0001	0.643	Large
S2-20	SEA_{10}	<0.0001	<0.0001	<0.0001	0.619	Large
S1-25	σ_{10}	<0.0001	<0.0001	<0.0001	0.914	Large
S1-25	W_5	<0.0001	<0.0001	<0.0001	0.724	Large
S1-25	W_{10}	<0.0001	<0.0001	<0.0001	0.859	Large
S1-25	SEA_5	<0.0001	<0.0001	<0.0001	0.475	Large
S1-25	SEA_{10}	<0.0001	<0.0001	<0.0001	0.635	Large
S2-25	σ_{10}	<0.0001	<0.0001	<0.0001	0.924	Large
S2-25	W_5	<0.0001	<0.0001	<0.0001	0.808	Large
S2-25	W_{10}	<0.0001	<0.0001	<0.0001	0.891	Large
S2-25	SEA_5	<0.0001	<0.0001	<0.0001	0.685	Large
S2-25	SEA_{10}	<0.0001	<0.0001	<0.0001	0.785	Large

Table A2. S1 vs. S2 pairwise contrasts (Welch *t*-test) for $\rho_{nominal} = 20 \text{ kg/m}^3$.

Metric	Recycled Content [%]	<i>t</i>	<i>p</i>	Significance	<i>d</i>	Direction
σ_{10}	5	−2.30	0.029	*	−0.86	S2 > S1
σ_{10}	10	+3.07	0.005	**	+1.20	S1 > S2
σ_{10}	25	+4.57	0.0001	***	+1.68	S1 > S2
σ_{10}	50	+1.67	0.131	n.s.	+0.87	S1 > S2
W_5	5	+1.17	0.252	n.s.	+0.43	S1 > S2
W_5	10	+3.09	0.005	**	+1.21	S1 > S2
W_5	25	+2.92	0.007	**	+1.08	S1 > S2
W_5	50	+1.87	0.086	n.s.	+0.93	S1 > S2
W_{10}	5	−0.38	0.705	n.s.	−0.14	S2 > S1
W_{10}	10	3.47	0.002	**	+1.36	S1 > S2
W_{10}	25	3.78	0.0008	***	+1.39	S1 > S2
W_{10}	50	1.88	0.091	n.s.	+0.97	S1 > S2
SEA_5	5	+3.25	0.004	**	+1.18	S2 > S1
SEA_5	10	+3.34	0.003	**	+1.31	S1 > S2
SEA_5	25	+3.11	0.004	**	+1.15	S1 > S2
SEA_5	50	+1.93	0.079	n.s.	+0.95	S1 > S2
SEA_{10}	5	1.91	0.069	n.s.	+0.70	S1 > S2
SEA_{10}	10	4.42	0.0002	***	+1.73	S1 > S2
SEA_{10}	25	4.39	0.0002	***	+1.61	S1 > S2
SEA_{10}	50	1.93	0.085	n.s.	+1.01	S1 > S2

(* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; n.s.: not significant).**Table A3.** S1 vs. S2 pairwise contrasts (Welch *t*-test) for $\rho_{nominal} = 25 \text{ kg/m}^3$.

Metric	Recycled Content [%]	<i>t</i>	<i>p</i>	Significance	<i>d</i>	Direction
σ_{10}	5	+0.53	0.599	n.s.	+0.21	S1 > S2
σ_{10}	10	−1.66	0.113	n.s.	−0.69	S2 > S1
σ_{10}	25	−2.75	0.011	*	−1.01	S2 > S1
σ_{10}	50	+6.91	<0.0001	***	+2.82	S1 > S2
W_5	5	+0.79	0.440	n.s.	+0.31	S1 > S2
W_5	10	−0.84	0.417	n.s.	−0.37	S2 > S1
W_5	25	−1.33	0.195	n.s.	−0.49	S2 > S1
W_5	50	+8.46	<0.0001	***	+3.45	S1 > S2
W_{10}	5	+0.78	0.446	n.s.	+0.30	S1 > S2
W_{10}	10	−0.91	0.378	n.s.	−0.40	S2 > S1
W_{10}	25	−2.14	0.042	*	−0.78	S2 > S1
W_{10}	50	+8.39	<0.0001	***	+3.43	S1 > S2
SEA_5	5	+0.76	0.455	n.s.	+0.30	S1 > S2
SEA_5	10	−0.62	0.545	n.s.	−0.28	S2 > S1
SEA_5	25	+0.54	0.597	n.s.	+0.20	S1 > S2
SEA_5	50	+6.48	<0.0001	***	+2.65	S1 > S2
SEA_{10}	5	+0.72	0.477	n.s.	+0.28	S1 > S2
SEA_{10}	10	−0.51	0.620	n.s.	−0.22	S2 > S1
SEA_{10}	25	+0.83	0.416	n.s.	+0.30	S1 > S2
SEA_{10}	50	+6.28	<0.0001	***	+2.56	S1 > S2

(* $p < 0.05$; *** $p < 0.001$; n.s.: not significant).

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