

## Article

# Quantifying the Geometric Thermal Benefit of 3D Concrete Printed Cavity Walls: Introducing the Thermal Effectiveness Index

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## Abstract

Three-dimensional concrete printing (3DCP) enables the fabrication of wall sections with internal cavities that are impractical to form with conventional methods. Although individual studies demonstrate that cavity geometry influences thermal resistance, the magnitude of this effect has not been quantified on a common basis across the literature. This paper introduces the Thermal Effectiveness Index (TEI), defined as the ratio of the theoretical U-value of a solid concrete wall (calculated using the material's actual thermal conductivity) to the reported U-value, in order to isolate the purely geometric contribution to thermal performance. A structured extraction from 24 Scopus-indexed articles yielded an analysis dataset of 255 variants from 23 articles (after the exclusion of one study whose composite mix made the geometric effect inseparable from material substitution), spanning 17 typology categories. Results show that standard rectangular air cavities perform worse than solid printed counterparts of the same material (median TEI = 0.56 versus 1.00 for solid walls) due to internal convection and thermal bridging, whereas sinusoidal infills with post-printed insulation reach a median TEI of 8.9 (18 variants from a single study, so the magnitude requires independent replication). These patterns are descriptive; an article-level sensitivity check indicates that the number of independent studies per wall-type group is not yet sufficient for confirmatory statistical inference. A compliance analysis against five building energy codes showed that only 22% of variants meet the  $0.30 \text{ W}/(\text{m}^2 \text{ K})$  threshold, in line with the component-based U-value criteria specified in the Passive House Institute's EnerPHit Standard for building retrofits and warm-climate classifications, as opposed to the more stringent  $\leq 0.15 \text{ W}/(\text{m}^2 \text{ K})$  requirement applicable to new construction in temperate climates.



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## 1. Introduction

The transition toward climate-neutral, resource-efficient and resilient construction practices is one of the key challenges facing modern society. In this context, the building sector is responsible for approximately 37% of global energy-related carbon dioxide emissions, a substantial share of which originates from heat transfer through the envelope [1]. Reducing the thermal transmittance of walls is therefore a direct lever for lowering both

operational energy demand and the associated carbon footprint [2]. Three-dimensional concrete printing (3DCP) offers a distinctive advantage in developing green materials and energy-efficient solutions for the built environment: it can produce wall cross-sections with internal cavities, zigzag webs, sinusoidal paths and honeycomb-like infills in a single fabrication pass, without formwork [3]. The benefits are not only geometric: a recent techno-economic assessment of modular 3D-printed housing reports reductions of roughly 20–30% in upfront construction cost, alongside shorter build times and less material waste [4]. By integrating smart geometries, these innovative materials and technologies support the shift toward more eco-efficient concrete and low-carbon construction systems.

A growing body of experimental and computational work has explored how these internal geometries affect thermal resistance. Pessoa et al. [5] and Moelich et al. [6] investigated heat transfer through printed wall sections with different void patterns, while Bianchi et al. [7] combined thermal simulation with life-cycle assessment. Ravula et al. [8] and Suntharalingam et al. [9] examined rectangular-cavity and triangular-void walls in parametric computational studies. Briels et al. [10] characterised kelvin-cell configurations, and Briels et al. [11] investigated hexagonal infill patterns. Mansouri et al. [12,13] applied conjugate heat-transfer analysis to printed sections, and He et al. [14] quantified energy-saving potential at the building scale. Marais and van Zijl [15] computationally assessed cavity-wall thermal performance with finite-element analysis, validating their model against published hot-box data, while Sun et al. [16] contributed experimental U-value measurements and Xing et al. [17] assessed the thermal impact of print-path discontinuities. More recent work continues to refine these geometries; for instance, Iozzino et al. [18] parametrically optimised sinusoidal-partition foamed-concrete blocks and found that porosity governs the steady-state U-value, with the internal print topology mainly adjusting the dynamic, periodic thermal response. General reviews have catalogued the technology landscape [19–22]. These catalogues remain valuable, but the thermal benefit of cavity geometry in 3DCP walls is typically reported in each primary study relative to its own solid reference using study-specific geometries, mix designs and measurement methods; a shared, thickness- and material-normalised basis that would permit direct comparison across studies is not commonly available.

This gap matters for two reasons. First, without a common metric, the question “how much does a given cavity geometry actually improve thermal performance relative to a solid wall of the same thickness?” cannot be answered by comparing results across studies. Second, the absence of a unified dataset prevents designers from assessing whether specific 3DCP typologies comply with national or regional building energy codes and life-cycle performance frameworks, such as the Passive House standard [23], the EPBD methodologies (e.g., EN ISO 52016 [24]), ASHRAE 90.1 [25] or the updated Turkish TS 825:2024 [26]. Both points limit the practical adoption of these energy-efficient geometries at the design stage. Addressing them requires reconciliation of the existing, fragmented evidence base on a common basis rather than generation of a further isolated set of geometries: the main obstacle is the incommensurability of results reported across studies that use different thicknesses and mix conductivities and measurement conventions; a single new simulation set, however internally consistent, would add one more non-comparable data point rather than resolve that fragmentation. In contrast, a cross-study synthesis places the geometric benefit on a shared metric and also exposes the reporting gaps that hold back design-stage adoption.

This paper addresses this gap through three contributions. First, it introduces the Thermal Effectiveness Index (TEI), which normalises U-values against a solid-concrete reference at matched thickness, isolating the geometric contribution to thermal performance. Second, it assembles a cross-study dataset from 24 articles, compares TEI distributions across wall-type categories and tests whether the differences are statistically significant

using Kruskal–Wallis and pairwise Mann–Whitney tests. Third, it maps the extracted U-values against five building energy standards, quantifying the proportion of variants that satisfy each compliance threshold.

## 2. Materials and Methods

### 2.1. Literature Search and Data Extraction

The literature corpus was assembled through an advanced Scopus search combining three Boolean blocks: (i) technology identifiers (“3D concrete print\*”, “3DCP”, “additive manufacturing of concrete”), (ii) element scope (wall, building envelope, panel, facade) and (iii) performance domains (thermal, energy, LCA, carbon footprint, topology, geometry, cavity). Results were restricted to journal articles and reviews published after 2018 in English. The search, conducted in January 2026, returned 123 records.

Screening followed the PRISMA 2020 guidelines (Figure 1) and proceeded in two stages. First, an algorithmic filter computed TF-IDF cosine similarity (unigram–bigram features, English stop-words removed, minimum document frequency of two) between each abstract and a set of ten anchor articles known to report both geometry and thermal data for printed wall sections. A deliberately permissive cosine-similarity threshold of 0.10 was applied to exclude 62 records whose abstracts shared little vocabulary with the thermal–geometric domain. The threshold was set low by design, favouring recall over precision: it acts as a coarse first-pass filter rather than the decisive inclusion criterion. It was calibrated to the lower tail of the score distribution, where a gap separated the relevant abstracts from a tail of records dominated by unrelated vocabulary (e.g., pavements, pedestrian bridges and robotic control). Because every record passing this pre-filter was re-evaluated first by a manual context filter, then by full-text eligibility assessment, the exact threshold value has little effect on the final set: it only sets how many off-topic abstracts are removed automatically before human screening, not which articles are ultimately included. Relaxing the threshold would merely pass additional low-similarity records to the manual context filter (which already removed 37 borderline records on topical grounds), whereas tightening it would risk discarding relevant work and was therefore avoided. The remaining 61 records passed through this context filter, which excluded studies whose primary topic fell outside the scope of this work, such as pedestrian bridges, robotic path planning, geopolymer binders without thermal data and non-wall structural elements. This step removed a further 37 records. The remaining 24 articles formed the analysis dataset; Table 1 summarises their characteristics. Each article was processed through four sequential stages: (i) document mapping; (ii) experiment-level extraction of geometry (wall type, thickness, and void ratio), material properties (density and thermal conductivity) and performance values (U-value, compressive strength, and GWP); (iii) evidence audit linking each extracted value to its specific source table, figure or text passage; and (iv) a structured quality appraisal in which each article was scored on study-design clarity, sample and geometry reproducibility, material reproducibility, clarity of the thermal method and table/figure usability, yielding an overall reproducibility score (0–100) and a risk-of-bias rating (low/moderate/high). Across the 23 retained articles, the risk of bias was rated low for all but one (rated as moderate), and the median reproducibility score was 96/100; these appraisal fields are retained in the open dataset (Table S1) so that the appraisal can be inspected.

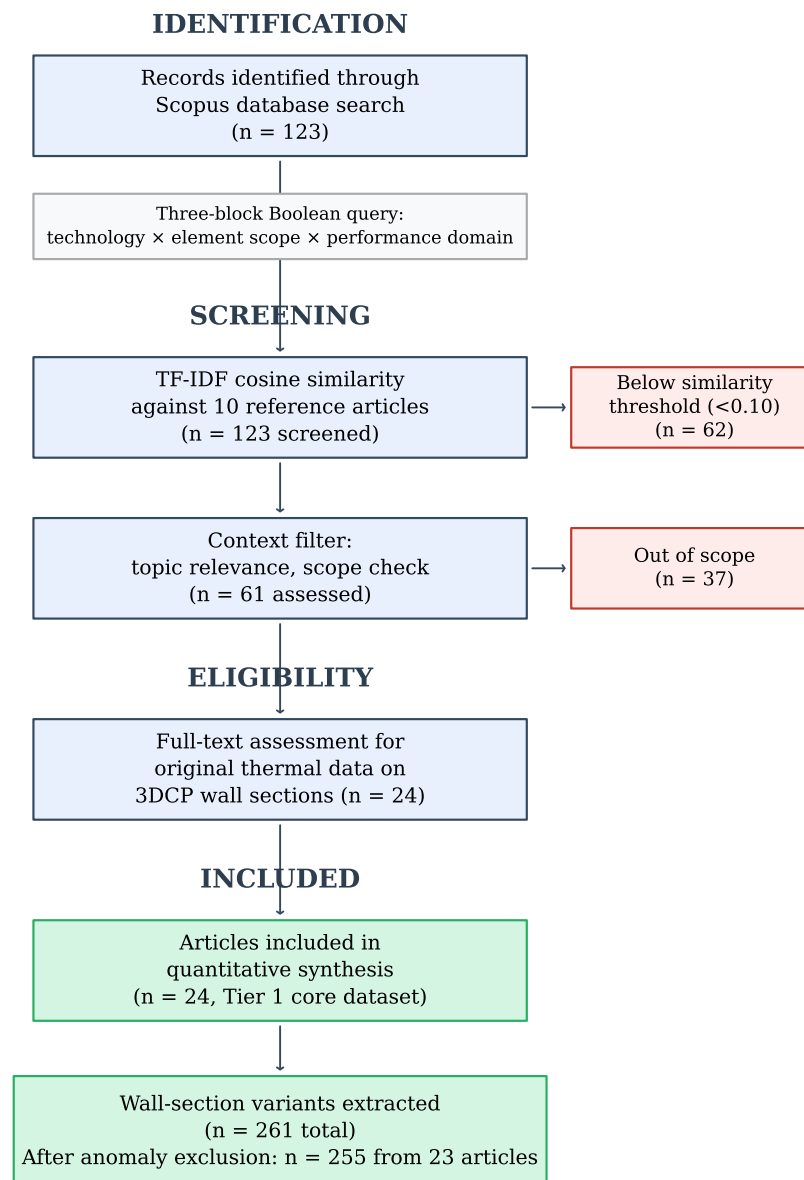
A preliminary pass through stages (i)–(iv) was carried out with the assistance of a custom Python 3.12 extraction pipeline that wrapped a large-language model (LLM) with schema-constrained prompting. The pipeline parsed each PDF into per-section text fragments, issued JSON-schema-validated requests for the four extraction stages (document map, experiments, evidence pointers, and quality flags), and stored the responses in a

per-article tabular structure suitable for downstream cross-checking. This first pass was intended as an automated scaffold; however, the resulting outputs contained frequent contextual misreadings, unit inconsistencies and misattributed values when compared against the source PDFs. Rather than accept these outputs, the first author subsequently performed a manual, article-by-article re-extraction using the original PDFs as the sole authoritative source. Every numerical entry, wall-type label, evidence pointer and derived quantity reported in this paper was checked against and, where necessary, reconstructed from the primary source. During this manual pass, each value was cross-checked against its evidence pointer, and discrepancies between the automated scaffold and the source were resolved in favour of the primary source; the 20 evidence conflicts and 11 low-confidence entries identified in this way are flagged in the open dataset so that values with residual uncertainty can be traced. Therefore, the final dataset released as the supplementary CSV file (Table S1) reflects this manual verification rather than the initial LLM pass; the LLM pipeline served only as an organisational scaffold and is not relied upon in any of the analyses reported below.

**Table 1.** Characteristics of the 24 included articles. Method codes: Sim. = numerical simulation; Exp. = experimental measurement; LCA = life-cycle assessment.

| Reference                   | Year | Primary Method | Wall Types | Extracted Variants | U Reported |
|-----------------------------|------|----------------|------------|--------------------|------------|
| Alzahrani & Alghamdi [27]   | 2022 | Sim.           | 7          | 14                 | Yes        |
| Bianchi et al. [7]          | 2024 | Sim. + LCA     | 2          | 25                 | Yes        |
| Briels et al. [11]          | 2023 | Sim. + Exp.    | 1          | 10                 | Yes        |
| Briels et al. [10]          | 2022 | Sim. + Exp.    | 1          | 2                  | Yes        |
| Chamatete & Yalçınkaya [28] | 2024 | Sim.           | 3          | 6                  | Yes        |
| Christen et al. [29]        | 2023 | Sim. + Exp.    | 1          | 2                  | No         |
| Dey et al. [30]             | 2025 | Sim. + Exp.    | 3          | 20                 | Yes        |
| Dey et al. [31]             | 2023 | Exp.           | 3          | 6                  | No         |
| Dziura et al. [32]          | 2023 | Sim. + Exp.    | 3          | 8                  | Yes        |
| He et al. [14]              | 2020 | Sim.           | 1          | 2                  | Yes        |
| Liu et al. [33]             | 2025 | Sim. + Exp.    | 4          | 10                 | Yes        |
| Ma et al. [34]              | 2022 | Exp.           | 1          | 4                  | No         |
| Mansouri et al. [12]        | 2026 | Sim. + Exp.    | 1          | 8                  | Yes        |
| Mansouri et al. [13]        | 2022 | Sim.           | 1          | 14                 | Yes        |
| Marais & van Zijl [15]      | 2021 | Sim.           | 2          | 10                 | Yes        |
| Moelich et al. [6]          | 2023 | Sim. + Exp.    | 3          | 10                 | Yes        |
| Pessoa et al. [5]           | 2025 | Sim. + Exp.    | 2          | 8                  | Yes        |
| Ramesh et al. [35]          | 2024 | Exp. + LCA     | 1          | 3                  | No *       |
| Ravula et al. [8]           | 2023 | Sim.           | 1          | 42                 | Yes        |
| Sun et al. [16]             | 2021 | Exp.           | 1          | 1                  | Yes        |
| Suntharalingam et al. [9]   | 2021 | Sim.           | 4          | 32                 | Yes        |
| Tamimi et al. [36]          | 2023 | Sim. + Exp.    | 4          | 4                  | Yes        |
| Wang et al. [37]            | 2025 | Sim. + Exp.    | 1          | 6                  | No *       |
| Xing et al. [17]            | 2025 | Sim. + Exp.    | 1          | 14                 | No         |

\* Note: Total U-value was not reported by Wang et al. [37] or Ramesh et al. [35]; in both cases, the U-value was imputed using ISO 6946 [2] from the reported thermal conductivity. Xing et al. [17] reported only the effective thermal conductivity ( $\lambda_{\text{eff}}$ ); the corresponding U-values were computed from  $\lambda_{\text{eff}}$  using the same reference. The wall-type count reflects the harmonised taxonomy used in this study (see Section 2.2) and may differ from the authors' own labelling. Extracted variant counts refer to the initial configurations entered into the dataset; the number of U-values plotted in subsequent analyses can be lower where individual variants are missing thickness, conductivity or U-value entries in the source article.



**Figure 1.** PRISMA 2020 flow diagram.

## 2.2. Data Harmonisation and Standardisation

Because the primary studies use heterogeneous geometric descriptors, boundary conditions and reporting formats, a structured harmonisation procedure was applied before any statistical analysis. Four families of standardisation steps are described below.

### 2.2.1. Wall-Type Taxonomy

A controlled vocabulary of 17 wall-type labels (e.g., *single-shell rectangular cavity*, *hollow-core triangular voids*, *sinusoidal infill with insulation*, and *hexagonal infill*) was defined *a priori* from a preliminary reading of the ten anchor articles used in the similarity screen. Where original authors named their infill pattern (e.g., ‘square zig-zag’ and ‘lattice’ in the work of Chamatete et al. [28]), their nomenclature was preserved and mapped to the nearest vocabulary entry. Unnamed configurations (e.g., those reported by Suntharalingam et al. [9]) were classified visually from published cross-sectional heat-flux maps into their morphological equivalents (rectangular, triangular or sinusoidal). Variants whose geometry could not be mapped unambiguously were classified as *other* (43 variants, 17%); these are retained in the dataset but excluded from wall-type-specific statistical tests to avoid

misclassification bias. The full set of categories, grouped by morphological family, is summarised in Table 2; the complete taxonomy assignment for every variant is recorded in the wall\_type column of the open dataset (Table S1) so that the classification step is auditable and reproducible [38–41].

**Table 2.** The 17-category wall-type taxonomy applied to the harmonised dataset, grouped by morphological family, with the number of variants in each category (*n*).

| Family       | Wall Type                        | Morphological Description                                             | <i>n</i> |
|--------------|----------------------------------|-----------------------------------------------------------------------|----------|
| Reference    | Solid                            | Monolithic printed/cast section; no internal void                     | 31       |
| Rectangular  | Single-shell rectangular cavity  | Two shells enclosing one row of rectangular air cells with cross-webs | 58       |
|              | Single-shell cavity + insulation | As above, cavity filled with post-printed insulation                  | 8        |
|              | Double-shell rectangular cavity  | Central septum forming two rows of rectangular cells                  | 10       |
|              | Straight-web infill              | Two shells joined by straight perpendicular webs                      | 2        |
| Angular      | Hollow-core triangular voids     | Diagonal webs forming a row of triangular voids                       | 43       |
|              | Zigzag infill                    | Single zig-zag web spanning the cavity                                | 3        |
| Wave         | Sinusoidal infill                | Sine-wave web between two shells                                      | 13       |
|              | Sinusoidal infill + insulation   | Sinusoidal print path with post-printed insulation fill               | 18       |
| Cellular     | Hexagonal infill                 | Honeycomb of hexagonal cells                                          | 11       |
|              | Diamond infill                   | Rhombic (diamond) lattice cells                                       | 1        |
|              | Kelvin cell                      | Truncated-octahedron unit cells                                       | 2        |
|              | Lattice infill                   | Crossing-diagonal lattice                                             | 2        |
| Reinforced   | Truss-reinforced                 | Triangulated truss web between chords                                 | 3        |
|              | Ladder-reinforced                | Central rail with horizontal rungs                                    | 3        |
| Composite    | Sandwich panel                   | Two concrete skins over a continuous insulating core                  | 4        |
| Unclassified | Other                            | Geometry not unambiguously mappable to one morphology                 | 43       |

### 2.2.2. Thermal Transmittance Normalisation

Reported U-values fall into three classes that were harmonised to a common basis. (i) *Surface-to-surface conductance* ( $\Lambda$ , W/(m<sup>2</sup> K)) are reported when experimental setups use guarded hot-box or heat-flow-meter measurements under steady-state gradients without explicit surface films (e.g., Liu et al. [33]). These were converted to total thermal transmittance via

$$U_{\text{norm}} = \frac{1}{(1/\Lambda) + R_{si} + R_{se}}, \quad (1)$$

using the standard vertical-wall surface resistances of  $R_{si} = 0.13$  and  $R_{se} = 0.04$  m<sup>2</sup> K/W, as prescribed by EN ISO 6946:2017 [2]. (ii) *Effective thermal conductivity* ( $\lambda_{\text{eff}}$ ) is reported in place of U for some cavity sections (e.g., Xing et al. [17]), converted to U via the ISO 6946 one-dimensional relation with the reported total thickness (*d*), i.e.,  $U = 1/(R_{si} + d/\lambda_{\text{eff}} + R_{se})$ . (iii) *Missing U-values*, accompanied by reported  $\lambda$  and *d* (Wang et al. [37]; Ramesh et al. [35]), were imputed using the same ISO 6946 expression for a solid layer; these entries are flagged as imputed in the accompanying open dataset.

### 2.2.3. Variable-Thickness Profiles

For walls with a continuously varying cross-section, a single “thickness” value is not unique, and the choice affects the solid-reference U-value entering Equation (4). The only such case in the present corpus is the slanted east wall of Mansouri et al. [12], whose thickness decreases linearly from 1200 mm at the base to 350 mm at the top

( $H = 3.75$  m). The area-averaged transmittance under the parallel heat-flow path assumption of EN ISO 6946 is

$$U_{\text{avg}} = \frac{1}{H} \int_0^H \frac{\lambda}{d(h)} dh, \quad (2)$$

which, for a linear taper of  $d(h) = d_{\text{max}} - (d_{\text{max}} - d_{\text{min}}) h/H$ , admits an analytically equivalent uniform thickness, i.e.,

$$d_{\text{eq}} = \frac{d_{\text{max}} - d_{\text{min}}}{\ln(d_{\text{max}}/d_{\text{min}})}. \quad (3)$$

Equation (3) is the logarithmic mean of the two extremes and returns the value that, when substituted into the one-dimensional ISO 6946 formula, reproduces  $U_{\text{avg}}$ . For Mansouri's geometry,  $d_{\text{eq}} = 850 / \ln(1200/350) \approx 690$  mm. Using the arithmetic mean (775 mm) instead would overstate the average thermal resistance of the solid reference and bias the TEI by roughly 10%; retaining the maximum thickness (1200 mm) would produce a bias exceeding 30%. Therefore, the equivalent thickness of 690 mm is applied to the two slanted-wall configurations reported by the authors in the harmonised dataset.

#### 2.2.4. Anomaly Exclusion

Variants outside plausible physical bounds (thickness  $< 40$  mm or GWP  $< 1.0$  kg CO<sub>2</sub>eq/m<sup>2</sup>) were excluded. All six variants from Wang et al. [37] were also removed because the study used Hollow Glass Microspheres (HGMAEC), which alter the bulk material conductivity to the point where geometric isolation is no longer meaningful. After these exclusions, the final analysis dataset contains 255 variants from 23 articles.

Table 3 summarises how the main sources of heterogeneity across the primary studies (differing geometric descriptors, boundary-condition conventions and reporting formats and incomplete data) were reconciled onto a common basis before any statistical comparison. Each rule is deterministic and recorded in the open dataset, so the transformation applied to every variant can be traced.

**Table 3.** Summary of the data-harmonisation rules applied to reconcile heterogeneity across the primary studies.

| Heterogeneity/Reporting Issue                                                                   | Applied Harmonisation Rule                                                                     | Basis       |
|-------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|-------------|
| Inconsistent wall-type nomenclature                                                             | Mapped to a 17-label controlled vocabulary (Table 2); unmappable cases flagged as <i>other</i> | This study  |
| Surface-to-surface conductance ( $\Lambda$ ) reported instead of total $U$                      | Converted via Equation (1) using standard surface films                                        | EN ISO 6946 |
| Effective conductivity ( $\lambda_{\text{eff}}$ ) reported instead of $U$                       | $U = 1 / (R_{si} + d / \lambda_{\text{eff}} + R_{se})$                                         | EN ISO 6946 |
| $U$ missing but $\lambda$ and $d$ reported                                                      | Imputed via the solid-layer ISO relation; entry flagged as imputed                             | EN ISO 6946 |
| Continuously varying cross-section thickness                                                    | Logarithmic-mean equivalent thickness, Equation (3)                                            | EN ISO 6946 |
| Anisotropic/directional conductivity (P/D/T)                                                    | $\lambda$ matched to the heat-flow direction of the reported $U$                               | [42]        |
| Divergent void-ratio descriptors (cavity%, solid%, air proportion)                              | Harmonised to a single void-ratio field where derivable                                        | This study  |
| Non-concrete/composite mix (e.g., HGM microspheres)                                             | Excluded: geometric isolation no longer valid                                                  | This study  |
| Physically implausible entries ( $d < 40$ mm, GWP $< 1.0$ kgCO <sub>2</sub> eq/m <sup>2</sup> ) | Excluded as anomalies                                                                          | This study  |

### 2.3. Thermal Effectiveness Index

To isolate the geometric contribution from material composition effects, the theoretical U-value of a monolithic concrete wall of the same total thickness was computed using the actual material thermal conductivity ( $\lambda_{\text{actual}}$ ). In 3DCP elements, thermal conductivity and other thermophysical properties are known to vary spatially and to exhibit anisotropy with respect to the printing (P), deposition (D) and transverse (T) directions [42]; wherever the source article reported a directional  $\lambda$ , the value used here corresponds to the heat-flow direction of the reported U-value measurement. The Thermal Effectiveness Index (TEI) is defined as

$$\text{TEI} = \frac{U_{\text{ref\_solid}}(d, \lambda_{\text{actual}})}{U_{\text{actual}}}, \quad (4)$$

where  $U_{\text{ref\_solid}}$  is the theoretical U-value of a monolithic concrete wall of the same total thickness ( $d$ ), computed using the *actual material thermal conductivity* ( $\lambda_{\text{actual}}$ ) reported for that specific variant and ISO 6946 surface resistances ( $R_{si} = 0.13 \text{ m}^2 \text{ K/W}$ ,  $R_{se} = 0.04 \text{ m}^2 \text{ K/W}$ ) [2]:

$$U_{\text{ref\_solid}} = \frac{1}{R_{si} + d/\lambda_{\text{actual}} + R_{se}}. \quad (5)$$

By construction, both terms in Equation (4) use the same  $\lambda_{\text{actual}}$ , so any difference in mix conductivity between studies cancels out, and the index reflects the geometry alone. This is what allows walls printed from different mortars (whose absolute U-values are not directly comparable because material conductivity also affects the U-value) to be compared on a common, material-independent basis; the simulation in Section 4.2 isolates this conductivity dependence directly. Variants lacking a reported  $\lambda_{\text{actual}}$  are excluded from the TEI calculations. In addition, solid-wall variants whose U-value was, itself, imputed via Equation (5) are excluded from the TEI analysis because in that case, the numerator and denominator of Equation (4) are computed from the same formula, producing  $\text{TEI} = 1.0$  by construction rather than by measurement. This exclusion removes 6 imputed solid variants, leaving 19 solid variants with independently reported, simulated or analytically calculated U-values available for the TEI comparison. A TEI of 1.0 means the cavity geometry performs identically to a solid wall of the same material and thickness.  $\text{TEI} > 1$  indicates that internal geometry reduces thermal transmittance below the solid reference;  $\text{TEI} < 1$  suggests that convective currents within the cavity or conductive web bridges make the wall less insulating than the equivalent solid section.

### 2.4. Statistical Tests and Compliance Thresholds

Differences in TEI across wall types were assessed using the Kruskal–Wallis H test, followed by pairwise Mann–Whitney U tests with Bonferroni correction for groups with at least five observations. Because many variants originate from parametric sweeps within the same study and are therefore not fully independent, a sensitivity check was performed by first computing the median TEI per article within each wall-type group, then applying the Kruskal–Wallis test to these article-level medians. Reported U-values were compared against five code thresholds: a threshold of  $0.30 \text{ W}/(\text{m}^2 \text{ K})$ , in line with the component-based U-value criteria specified in the Passive House Institute’s EnerPHit Standard for building retrofits and warm-climate classifications [23,43,44], as opposed to the more stringent  $\leq 0.15 \text{ W}/(\text{m}^2 \text{ K})$  requirement applicable to new construction in temperate climates, a representative European threshold of  $0.50 \text{ W}/(\text{m}^2 \text{ K})$  (consistent with typical national implementations of the EPBD and the monthly calculation methodology of EN ISO 52016-1 [24]), ASHRAE 90.1 Climate Zone 5 ( $0.45 \text{ W}/(\text{m}^2 \text{ K})$ ) [25], and the recently updated Turkish standard TS 825:2024 [26], Annex A.2 of which specifies maximum recommended opaque-wall

U-values of 0.45 W/(m<sup>2</sup> K) for Zone 1 (Extreme Hot) and 0.40 W/(m<sup>2</sup> K) for Zone 2 (Hot); TS 825:2024. itself, is framed as a national adaptation of EN ISO 52016-1, so these thresholds sit within a consistent methodological family. All tests were conducted at  $\alpha = 0.05$ .

3. Results

3.1. Dataset Overview

The 24 screened articles initially yielded 261 wall-section configurations. Following the exclusion of six hollow-glass microsphere variants (Wang et al. [37]), 255 variants from 23 articles remained in the final dataset. Table 4 summarises data availability, and Figure 2 shows the reporting completeness for each article and performance field. Wall thickness and thermal conductivity are reported for more than 94% of variants, and thermal transmittance is reported for 89%, while embodied carbon remains sparse (14%).

Table 4. Data availability across key performance fields (255 variants, 23 articles).

| Performance Field     | Reported Variants | Source Articles | Coverage (%) |
|-----------------------|-------------------|-----------------|--------------|
| Wall thickness        | 239               | 20              | 94           |
| U-value               | 226               | 20              | 89           |
| Thermal conductivity  | 244               | 21              | 96           |
| Density               | 182               | 16              | 71           |
| Compressive strength  | 42                | 7               | 16           |
| Embodied carbon (GWP) | 35                | 4               | 14           |
| Void ratio            | 142               | 15              | 56           |

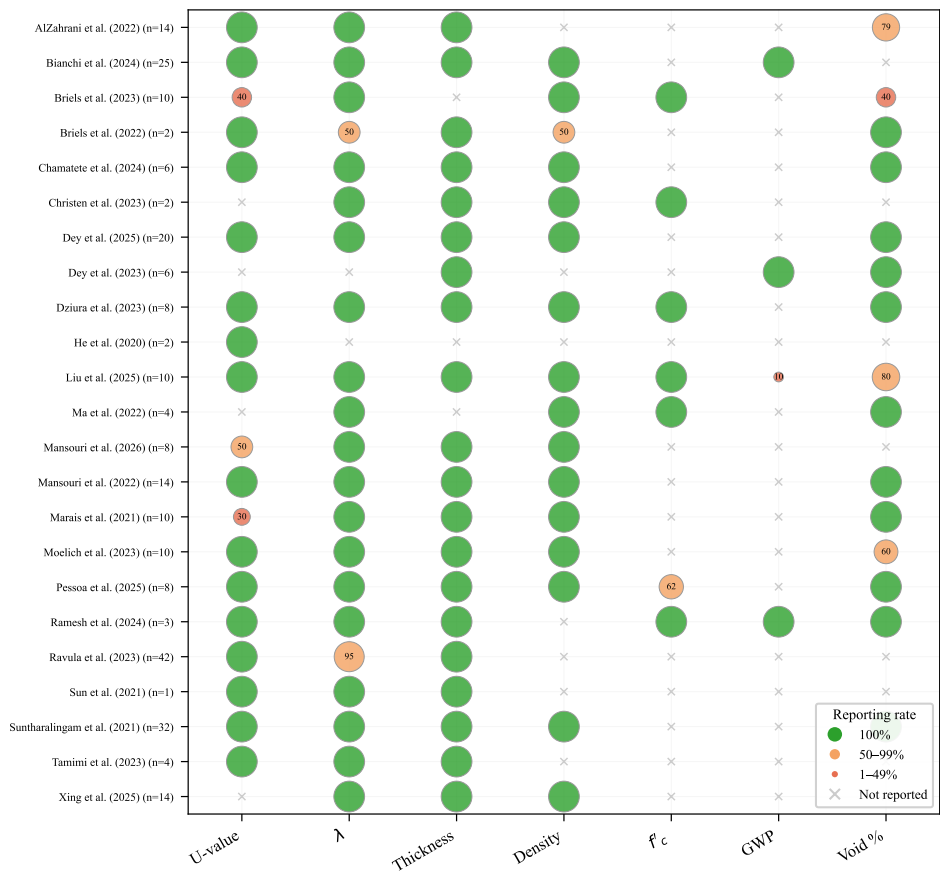
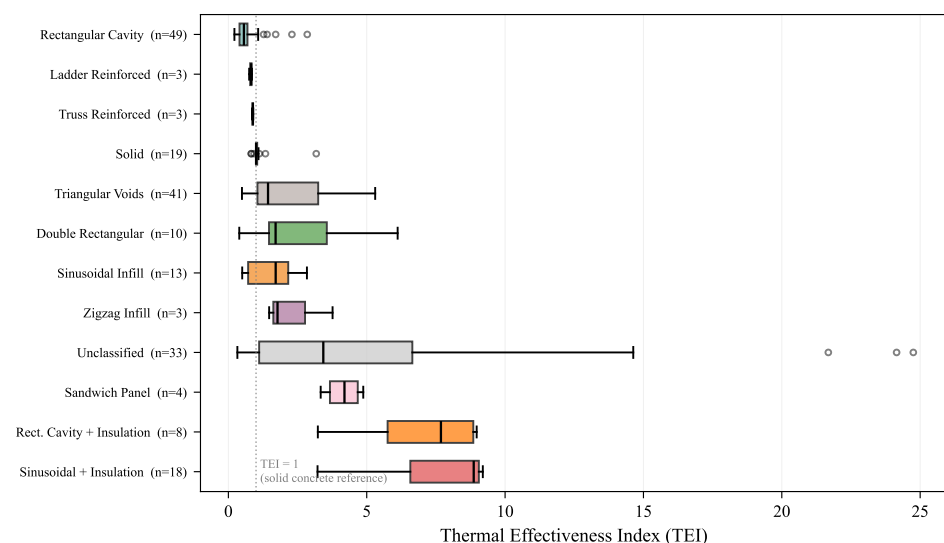


Figure 2. Data reporting completeness per article and performance field. Green circles indicate 100% coverage; coloured circles indicate partial coverage; crosses indicate no data reported.

### 3.2. Thermal Effectiveness by Wall Type

Figure 3 presents the TEI distribution for classified wall types with at least three observations; 6 imputed solid variants are excluded to avoid the circular-reference artefact described in Section 2.3. Sinusoidal infill with post-printed insulation [7] achieved the highest median TEI (8.9), indicating that these walls reduce thermal transmittance by roughly a factor of nine compared with a solid wall of the same thickness. Rectangular cavities with insulation reached a median TEI of 7.7. Zigzag infill walls yielded a median TEI of 1.8, and triangular-void walls, despite being the second most numerous category (41 variants from six articles [6,9,27,30,32,33]), showed a median TEI of 1.4, with a wide interquartile range reflecting substantial variation in void configuration. Rectangular-cavity walls without insulation yielded a median TEI of only 0.56, while solid walls reached a median TEI of 1.00 ( $n = 19$ ).

A variant-level Kruskal–Wallis test on categorised wall types indicated that TEI differs across geometries ( $H = 116.2$ ,  $p < 0.001$ , 11 groups with  $n \geq 3$ ). Because many variants come from parametric sweeps within the same study, they are not fully independent observations. When the test was repeated using article-level median TEI values, only four wall-type groups contained three or more contributing articles, and the difference was no longer statistically significant ( $H = 2.8$ ,  $p = 0.43$ ). The loss of significance is expected, given the small number of independent studies per group; nevertheless, the descriptive pattern remains clear: rectangular cavities without insulation (median TEI = 0.56) consistently fall below the solid baseline (median TEI = 1.00), whereas insulation-filled typologies cluster well above it.

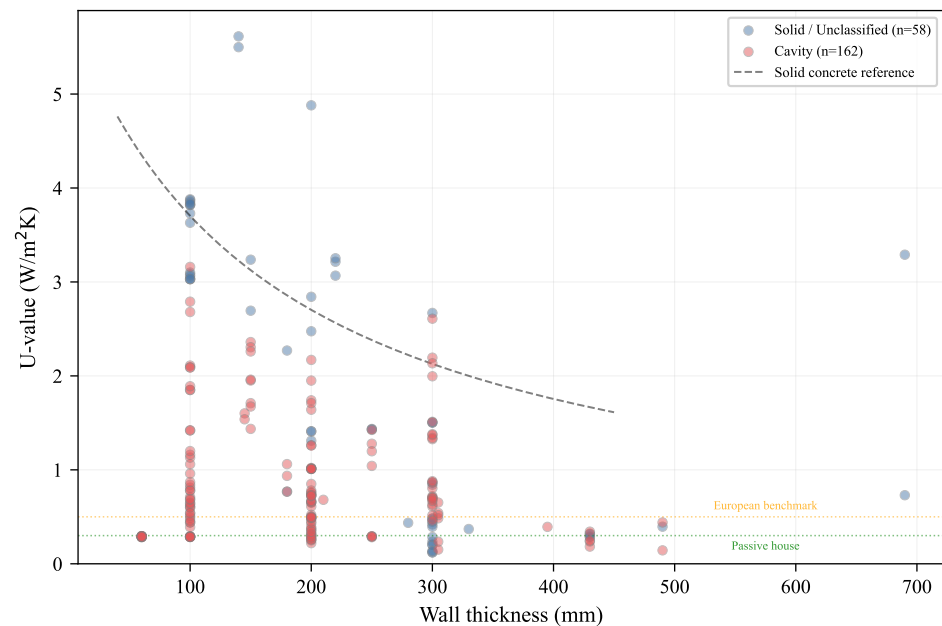


**Figure 3.** Thermal Effectiveness Index (TEI) by wall type. TEI = 1 corresponds to solid concrete. Higher values indicate greater geometric benefit. Sample sizes are in parentheses.

### 3.3. Thickness–U-Value Relationship

Figure 4 plots wall thickness against the U-value for 220 variants with both fields reported. The dashed line represents the theoretical U-value of a solid concrete wall. Solid walls cluster around this line, confirming that their thermal resistance is governed primarily by the conductive path length. Cavity walls scatter well below the reference, particularly in the 150 to 300 mm range, where different infill geometries produce U-values spanning from 0.14 to above  $2 \text{ W}/(\text{m}^2 \text{ K})$ . The wide scatter within the cavity group indicates that the wall-type label and overall thickness alone are insufficient to predict the U-value; detailed geometric parameters such as the void ratio, infill wavelength and shell thickness would

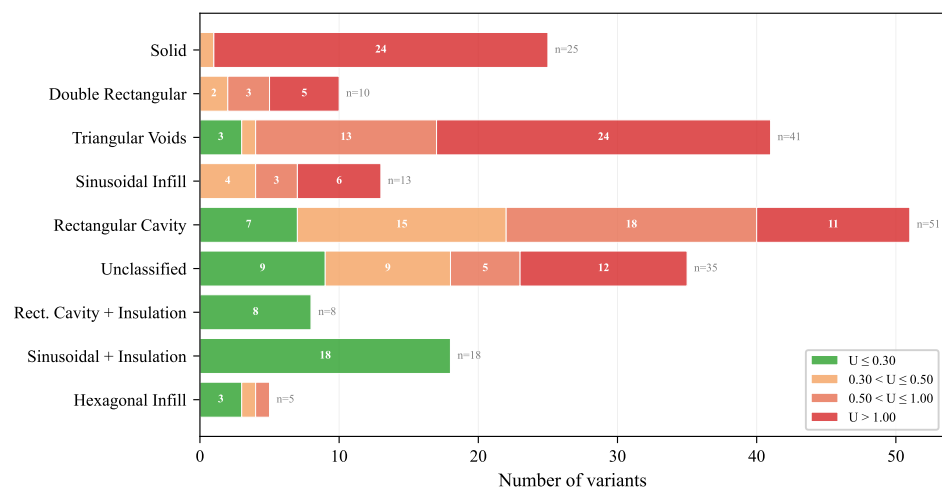
be needed for a reliable predictive model, yet the void ratio was reported in only 56% of all variants.



**Figure 4.** Wall thickness versus U-value for 220 variants. The dashed line shows the ISO 6946 prediction for solid concrete, and the horizontal dotted lines mark the passive-house and European code thresholds. The two variants at 690 mm are the slanted east wall of Mansouri et al. [12], represented by its logarithmic-mean equivalent thickness (Section 2.2).

### 3.4. Building-Code Compliance

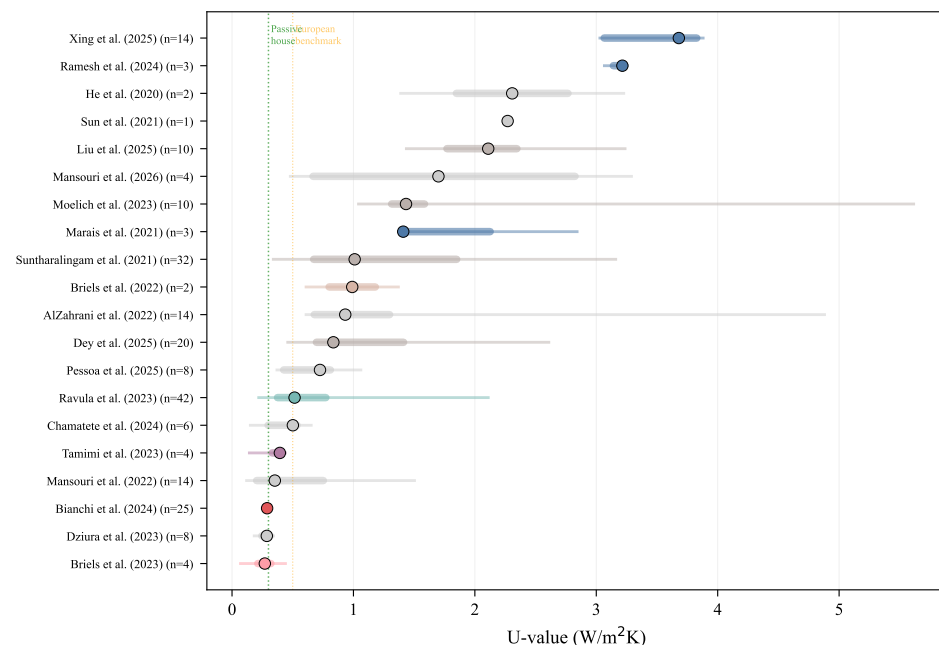
Figure 5 maps the number of variants satisfying different U-value bands for each wall type with at least five reported values. Among the 226 variants with U-values, 50 (22%) met the 0.30  $W/(m^2 K)$  EnerPHit threshold, while 85 (38%) satisfied the European benchmark of 0.50  $W/(m^2 K)$ . For the updated Turkish standard (TS 825:2024), 64 variants (28%) satisfied Zone 2 (Hot), and 73 (32%) satisfied Zone 1 (Extreme Hot). All 18 sinusoidal-infill-with-insulation variants and all 8 rectangular-cavity-with-insulation variants complied at the European level. Among the 51 single-shell rectangular-cavity variants without insulation, 22 (43%) complied, while only one of 25 solid-wall variants reached that level.



**Figure 5.** Building-code compliance by wall type, shown as stacked variant counts across four U-value bands.

### 3.5. Cross-Study Variation

Figure 6 presents a forest-style plot of the U-value ranges of the extracted variants for the 20 articles that reported or allowed computation of thermal transmittance. Across these variants, the per-article median spans more than an order of magnitude, from  $0.27 \text{ W}/(\text{m}^2 \text{ K})$  [11] to  $3.68 \text{ W}/(\text{m}^2 \text{ K})$  [17]. For three articles, the median of the extracted variants falls at or below the passive-house threshold: those of Bianchi et al. [7] (sinusoidal with insulation,  $0.29 \text{ W}/(\text{m}^2 \text{ K})$ ), Briels et al. [11] (hexagonal infill,  $0.27 \text{ W}/(\text{m}^2 \text{ K})$ ) and Dziura et al. [32] (mixed infill patterns,  $0.29 \text{ W}/(\text{m}^2 \text{ K})$ ). These article-level medians describe the extracted variants rather than the full distributions of the original studies, which, for large parametric sweeps, can differ substantially: the extracted hexagonal configurations of Briels et al. are drawn from a 4500-variant optimization in which only about 7% of cases meet its combined thermal and structural targets, so they represent the better-performing end of that study. Ravula et al. [8] provided the largest batch (42 variants,  $U = 0.22$  to  $2.11 \text{ W}/(\text{m}^2 \text{ K})$ ), while Suntharalingam et al. [9] contributed 32 variants ( $U = 0.34$  to  $3.16 \text{ W}/(\text{m}^2 \text{ K})$ ).



**Figure 6.** Forest plot of the U-value ranges of the extracted variants per article. Circles mark the median; thick bars span the interquartile range; thin lines extend to the minimum and maximum.

## 4. Discussion

### 4.1. Geometric Thermal Advantage and Sensitivity

The TEI analysis isolates the geometric effect of cavity morphologies from material conductivity by normalising each variant against a solid wall of identical thickness and mix composition. When this normalisation is applied, typical uninsulated rectangular cavities (median TEI = 0.56) fall below the solid baseline (median TEI = 1.00,  $n = 19$  after excluding imputed values). This result implies that internal air convection and conductive web bridging can offset the potential benefit of the enclosed air space, particularly when the base concrete already has a low conductivity ( $\lambda < 0.4 \text{ W}/\text{mK}$ ). By contrast, sinusoidal infills combined with post-printed insulation reach a median TEI of 8.9, indicating that complex print paths paired with secondary insulation can deliver large thermal gains. The 18 sinusoidal-with-insulation variants originate from a single study (Bianchi et al. [7]). Although the post-printed insulation fill is likely the primary driver of the high TEI, the

generalisability of this finding requires confirmation from independent studies. The post-printing step also changes the production process relative to print-only typologies.

The large spread within each category (particularly rectangular cavities, with TEI values ranging from 0.22 to 6.1) suggests that the infill geometry interacts strongly with design parameters not captured by the wall-type label alone. The most influential of these are the void-to-solid ratio, the wavelength of the infill pattern and whether additional insulation was placed inside the cavity. This finding aligns with that of Ravula et al. [8], who demonstrated that the U-value is highly sensitive to the aspect ratio of rectangular cavities, and with that of Suntharalingam et al. [9], who showed wide performance variation across minor geometric changes. Dziura et al. [32] similarly observed that different void aspect ratios yield U-values differing by a factor of two, consistent with the broad interquartile range seen in the present dataset.

To verify that these findings do not depend on the choice of each variant's own  $\lambda_{\text{actual}}$ , Table 5 reports median TEI values obtained by substituting a single fixed  $\lambda_{\text{ref}}$  for all variants (imputed solid variants excluded). Changing  $\lambda_{\text{ref}}$  from 0.8 to 1.2 W/(m K) shifts the absolute TEI values, but the cavity-to-solid ratio remains between 3.4 and 3.6 and always indicates that cavity geometries, on average, deliver a geometric benefit several times that of the solid baseline. The qualitative pattern is therefore stable under different reference choices.

**Table 5.** Sensitivity of median TEI to a fixed reference thermal conductivity (imputed solid variants excluded).

| $\lambda_{\text{ref}}$ (W/(m K)) | Cavity Median TEI | Solid Median TEI<br>( $n = 19$ ) | Ratio |
|----------------------------------|-------------------|----------------------------------|-------|
| 0.8                              | 3.6               | 1.0                              | 3.4   |
| 1.0                              | 4.1               | 1.2                              | 3.5   |
| 1.2                              | 4.5               | 1.3                              | 3.6   |

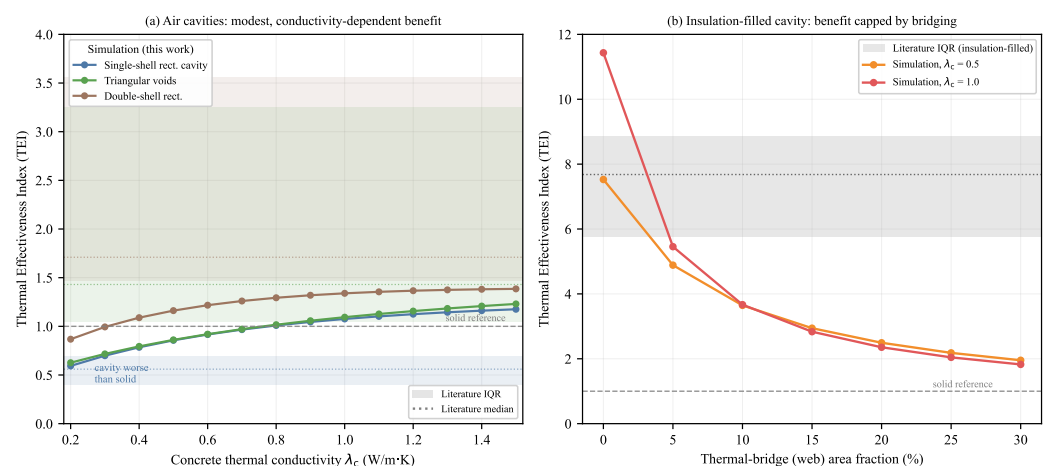
#### 4.2. Independent Numerical Verification

Because the literature U-values were obtained by heterogeneous methods (finite-element and CFD simulation, analytical calculation and experiment) that do not treat convection within the cavities on a common basis, one concern is whether the observed TEI patterns reflect this inconsistency rather than a real geometric effect. To address this, a set of canonical geometries was re-evaluated under a single, internally consistent method. We used a two-dimensional, finite-volume, steady-state conduction solver in which unventilated air cavities are represented by their EN ISO 6946 equivalent thermal resistance, which embeds conduction, convection and radiation in the enclosed air. This resistance is assigned from the contiguous cavity depth in the heat-flow direction, and the same surface films ( $R_{si} = 0.13$ ,  $R_{se} = 0.04 \text{ m}^2 \text{ K/W}$ ) are applied to every case. Two checks support the reliability of the results. First, for one-dimensional configurations, the solver recovers the analytical solid-wall U-value and the closed-form EN ISO 6946 series resistance of a layered cavity exactly. This is the expected behaviour of a conservative finite-volume scheme for layered media, and it verifies that the material resistances, the EN ISO 6946 cavity treatment and the surface-film boundary conditions are implemented correctly. Second, for the two-dimensional geometries with webs and triangular voids, where no closed-form solution exists, the computed U-values are grid-independent: refining the mesh from the  $160 \times 160$  grid used here to  $320 \times 320$  changed them by less than 1% (and by less than 0.05% for the rectangular-cavity geometries).

Figure 7 reports the simulated TEI alongside the corresponding literature distributions. For air-filled cavities (panel a), the simulated TEI is modest and rises monotonically with

concrete conductivity, from approximately 0.6 at  $\lambda_c = 0.2 \text{ W/(m K)}$  to about 1.2–1.4 at  $\lambda_c = 1.5 \text{ W/(m K)}$ , and it falls below unity for low-conductivity concrete. This reproduces, with an independent method, the main result of the literature synthesis. A single-shell rectangular air cavity gives a simulated TEI of 0.59 at  $\lambda_c = 0.2 \text{ W/(m K)}$ , which is close to the literature median of 0.56. Uninsulated cavities can therefore perform worse than a solid wall of the same low-conductivity material because the capped air-gap resistance is smaller than that of the concrete it displaces. When the same cavity is instead filled with insulation (panel b), the simulated TEI rises to 7–11 for a continuous fill but collapses towards  $\approx 2$  as the area fraction of conductive web bridges increases. The literature range for insulation-filled walls (interquartile range 5.8–8.9) corresponds to the lightly bridged regime, with the  $\lambda_c = 0.5 \text{ W/(m K)}$  continuous-insulation case (TEI = 7.5) falling squarely within it.

Because one method is applied across all geometries, this agreement suggests that the cross-study TEI patterns are not an artefact of inconsistent convection modelling in the source studies. It also has a practical implication: geometry alone gives little thermal benefit and can be detrimental at low conductivity, while the larger gains seen for insulation-filled typologies are obtained only when thermal bridging through the printed webs is kept small. The verification solver is provided as Supplementary Material so that the check can be reproduced.



**Figure 7.** Independent 2D heat-transfer simulation of canonical wall geometries compared with the literature-derived TEI. (a) Air-filled cavities: simulated TEI against concrete thermal conductivity, with the literature interquartile range (shaded) and median (dotted) for each category. (b) Insulation-filled cavity: simulated TEI against the thermal-bridge (web) area fraction for two concrete conductivities; the shaded band marks the literature interquartile range for insulation-filled walls.

#### 4.3. Influence of U-Value Determination Method

Distinguishing experimentally measured U-values from computed ones is important when interpreting the TEI because the two carry different levels of certainty. The method by which U-values were obtained varies across the dataset: 127 from finite-element or CFD simulations, 64 from analytical calculations, 18 from experimental measurements, 6 from ISO 6946 imputation and 11 from direct literature values or unspecified sources. Analytically calculated variants reach a median TEI of 6.4, largely because this subset includes the 18 insulation-filled sinusoidal configurations of Bianchi et al. [7], which skew the central tendency upward. Simulation-derived variants sit close to the solid reference (median TEI of 1.0), while experimentally measured variants show a median TEI of 1.4, which is slightly above the solid baseline and consistent with the modest geometric benefit expected for uninsulated cavity walls. The central observation is that the high-TEI region of the dataset is supported mainly by analytical calculations that incorporate insulation, while

the corresponding experimental and CFD evidence base for those same configurations is comparatively thin. In-situ measurements of insulation-filled printed sections would therefore strengthen the most optimistic part of the current TEI distribution.

#### 4.4. Compliance, Reporting Gaps and Design Implications

The compliance analysis provides a broader perspective than isolated case studies. Although individual variants reach U-values well below the passive-house threshold, only 22% of all variants meet that standard; compliance rises to 28% at TS 825:2024 Zone 2 ( $0.40 \text{ W}/(\text{m}^2 \text{ K})$ ) and to 38% at the European benchmark ( $0.50 \text{ W}/(\text{m}^2 \text{ K})$ ). A substantial fraction of 3DCP cavity configurations would therefore still require supplementary insulation to satisfy current regulations. Typology matters: sinusoidal infill with insulation and rectangular cavities with insulation both achieve 100% compliance at the European level, rectangular cavities without insulation comply at 43%, and only 4% of solid walls reach that benchmark. Infill typology and the option of post-printing insulation therefore dominate in terms of whether a given wall section can meet building energy codes without additional material layers. TS 825:2024 also introduces combined heating-and-cooling energy-demand limits (for example,  $70 \text{ kWh}/\text{m}^2 \cdot \text{year}$  for residential buildings in Zone 4), so future 3DCP envelope assessments will need to pair static U-value evaluation with dynamic response characterisation. That dynamic analysis lies beyond the steady-state scope of the present dataset.

The data completeness analysis also reveals a systemic fragmentation in the 3DCP wall literature. Volumetric parameters directly influencing thermal performance appear in various forms—‘Cavity %’ [30], ‘Solid %’ [11,32], ‘air proportion’ [33] or ‘void-to-footprint ratio’ [31]—without a unified standard, so an explicit void ratio was identified or directly derivable in only 56% of variants. Embodied carbon appeared in only four articles; Christen et al. [29] and Ma et al. [34] reported detailed material compositions that enabled downstream analysis, but most articles omit this information. This fragmentation prevents multi-criteria optimisation combining thermal and environmental objectives and limits the reproducibility of thermal simulations by third parties. We therefore recommend that future studies adopt a minimum reporting set: wall type (using a shared taxonomy), total thickness, void ratio, thermal conductivity, U-value with the determination method, density and compressive strength. A tiered minimum reporting set for cross-study reliability in 3DCP is developed in a companion study [45]. The structured extraction fields used in this study could serve as a template.

#### 4.5. Limitations

Several limitations should be noted. First, this study focuses exclusively on thermal performance. Increasing the void ratio to improve the TEI inevitably reduces the load-bearing cross-section and may compromise compressive strength and resistance to lateral loads. Parametric structural studies of 3DCP walls show that infill geometry governs both the moment of inertia and the buckling response under axial and lateral loads [46,47]. Cavity typologies that maximise thermal effectiveness therefore cannot be recommended in isolation from their mechanical consequences, which fabrication-aware structural-optimization frameworks are increasingly designed to address [48]. Compressive-strength data were available for only 16% of variants, which prevents a quantitative assessment of the thermal–structural trade-off within the present dataset. Future work should address this interaction explicitly, together with durability aspects such as moisture ingress and freeze–thaw exposure at internal cavity surfaces, which lie outside the present thermal-only scope. Second, many variants in the dataset originate from parametric sweeps within the same simulation model (e.g., 42 rectangular-cavity variants in the work of Ravula

et al. [8] and 32 variants in the study of Suntharalingam et al. [9]). These variants are not fully independent observations (a form of pseudo-replication), which inflates the effective sample size in the variant-level Kruskal–Wallis test. The article-level sensitivity check reported in Section 3.2 showed that the difference across wall types was no longer statistically significant when each study contributed a single median value, though the number of independent articles per group ( $\leq 6$ ) provides low statistical power. The TEI differences described here should therefore be read as descriptive patterns observed across the current literature rather than as confirmatory evidence of population-level effects. A separate cross-study reliability analysis quantifies the between-study (laboratory) component of this variability [45]. Third, 17% of variants could not be classified because the source articles described geometries ambiguously; these are excluded from wall-type-specific tests but remain in the overall dataset for the thickness and compliance analyses. Fourth, the ISO 6946 reference used for the TEI assumes one-dimensional heat flow, which may overestimate the U-value for cavity walls, where two-dimensional effects are significant; The TEI should therefore be regarded as a conservative lower bound for the geometric benefit. Fifth, the dataset is confined to the current published literature, which is biased toward certain wall types (rectangular cavities and triangular voids) and under-represents others (kelvin cells, diamond infill, and hexagonal cavities). Sixth, 56% of U-values are simulation-derived, and the experimental subset is small ( $n = 18$  with measured U-values); therefore, the reported TEI medians may reflect the broader parameter space explored in computational studies rather than physically demonstrated performance.

## 5. Conclusions

This study assembled a harmonised dataset from 24 peer-reviewed articles on 3D concrete printed walls and introduced the Thermal Effectiveness Index (TEI) to quantify the geometric contribution to thermal resistance on a common, thickness-independent basis.

When geometry is isolated from material conductivity, standard rectangular cavities without insulation perform worse than solid walls of the same material (median TEI = 0.56 versus 1.00) because internal air convection and web bridging outweigh the benefit of the enclosed air layer. Instead, the large thermal gains come from insulation-filled typologies, with sinusoidal infills reaching a median TEI of about 8.9. Because only a few independent studies have populated each wall-type group, these patterns should be read as descriptive findings that require corroboration, and the high-TEI region rests mainly on analytically computed insulated configurations rather than on direct experimental evidence.

Most current 3DCP wall configurations satisfy a passive-house U-value only after supplementary insulation, and the choice of infill typology strongly affects whether a wall can meet building energy codes. Progress is also limited by reporting gaps, as embodied carbon and the void ratio are documented for only a minority of variants. Future work should couple the TEI with life-cycle assessment and topology-level structural optimisation [20,48,49], prioritise in situ thermal measurements on full-scale printed panels (for which low-cost, non-contact infrared methods are emerging [50]), and extend the analysis to two-dimensional thermal bridging at web intersections.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/buildings16152946/s1>, Table S1: The comprehensive benchmark dataset of 3DCP cavity-wall variants (CSV).

**Author Contributions:** Conceptualization, S.Ö. and S.A.; methodology, S.Ö.; software, S.Ö.; validation, S.Ö. and S.A.; formal analysis, S.Ö.; data curation, S.Ö.; writing—original draft preparation, S.Ö.; writing—review and editing, S.Ö. and S.A.; visualization, S.Ö.; supervision, S.A. All authors have read and agreed to the published version of the manuscript.

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## Abbreviations

The following abbreviations are used in this manuscript:

|        |                                                                           |
|--------|---------------------------------------------------------------------------|
| 3DCP   | Three-dimensional concrete printing                                       |
| ASHRAE | American Society of Heating, Refrigerating and Air-Conditioning Engineers |
| CFD    | Computational fluid dynamics                                              |
| EPBD   | Energy Performance of Buildings Directive                                 |
| GWP    | Global warming potential                                                  |
| HGMAEC | Hollow glass microsphere aerated engineered cementitious composite        |
| ISO    | International Organization for Standardization                            |
| LCA    | Life-cycle assessment                                                     |
| PRISMA | Preferred Reporting Items for Systematic Reviews and Meta-Analyses        |
| TEI    | Thermal Effectiveness Index                                               |
| TF-IDF | Term frequency–inverse document frequency                                 |
| TS     | Turkish Standard (Türk Standardı)                                         |

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