Carbon Footprint of Natural Stone and Building Materials
天然石材與建材之碳足跡

(Prepared for Taiwan Marble Association / 為台灣區石礦製品工業同業公會編製)

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1. Executive Summary / 摘要

English

This document provides a bilingual overview of the carbon footprint (PCF) of natural stone and building materials, using A1 – A3 cradle-to-gate boundaries and a standardized functional unit. Key findings show:

- Natural stone’ s emissions mainly arise from quarrying and primary cutting, with finishing contributing less.
- Compared on the same unit (1 m² × 2 cm), stone has a significantly lower PCF than ceramic tile or cement render, while offering higher durability.
- Stone can be physically uninstalled and reused; metal fixings can be recycled, approaching zero construction waste.
- Artificial/composite materials cannot revert to raw state; C1 – C4 and D burdens are often underestimated.

中文

本文件提供天然石材與建材碳足跡（PCF）之雙語概述，依 A1 – A3 邊界及標準功能單位進行比較。主要發現如下：

- 天然石材的排放主要來自礦山開採與初步切割；後續拋光佔比更小。
- 以相同單位（1 m² × 2 cm）比較時，天然石材的碳足跡顯著低於瓷磚與水泥抹面，且耐久性更高。
- 石材可實體拆卸後再利用，金屬固定件可回收，接近零建廢。
- 人工/複合建材拆卸後難以回復原料態，C1 – C4 與 D 階段的排放常被低估。

2. Standards & Methodology / 標準與方法

2.1 生命週期邊界 / System Boundary

- **A1 原料供應**：礦山/原料取得；A2 運輸；**A3 製造**。
- **B 使用階段**（維護、清潔、翻新、壽命週期）；
- **C1 – C4 拆除與處置**（拆除、運輸、處理、最終處置）；
- **D 之外部效益**（回收、能源回收或替代效益）。

本文件的**主比較表鎖定 A1 – A3**，以減少場地、工法與壽命差異造成的偏差；並以第 5 章補充 C 與 D 階段之關鍵差異。

2.2 功能單位 / Functional Unit

- **1 m² × 2 cm 厚** 之完成面材料；體積 0.02 m³。
- 以密度（kg/m³）× 體積，求得**每 m² 的材料質量（kg）**，再乘以 **kg CO_2e/kg** 取得 **kg CO_2e/m²**。

2.3 國際標準 / International Standards

- **ISO 14067**（產品碳足跡）
- **EN 15804+A2**（建材環境產品宣告 EPD）
- **PCR / CFP-PCR**（品類規則；含日本 JEMAI/JP 系統）

2.4 主要資料來源 / Primary Data Sources

- **ICE Database v3.0**（University of Bath, UK）
- **Ecoinvent v3.9**（Switzerland, global LCI）
- **EPDs per EN 15804**（EU industry associations & manufacturers）
- **Japanese CFP/EPD system (JEMAI)**

實際引用將以最新可得之 EPD 與資料庫條目為準，並於最終版附錄完整列示。

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3. A1 – A3 PCF Comparison (Same Spec) / 碳足跡比較

Functional Unit / 功能單位：1 m² × 2 cm（A1 – A3，拋光或等同成品面 / Finished surface）

Material / 材料	PCF (kg CO_2e/kg)	Mass (kg)	Density (kg/m³)	PCF per 1 m² (kg CO_2e)	Notes / 註解
Wood (Timber, Softwood) / 天然木材（軟木/實木）	0.05 – 0.15	~12	~600	0.6 – 1.8	Biogenic carbon stored / 生物碳儲存；戶外耐久性有限
Natural Stone (Granite/Marble) / 天然石材（花崗岩/大理石）	0.12 – 0.25	~52	~2600	6 – 13	Quarrying dominates / 採礦階段佔比最高；切割拋光較小
Artificial Wood (MDF/Particle Board) / 人造木材（中纖板/刨花板）	0.25 – 0.35	~14	~700	3.5 – 5.0	Resin adhesives add emissions / 樹脂膠黏劑增加排放；耐久性不足
Clay Brick / 黏土磚	0.25 – 0.35	~38	~1900	9 – 13	Kiln-fired / 窯燒製程
Engineered Quartz (Quartz Composite) / 人造石英（石英複合材）	0.35 – 0.55	~44	~2200	15 – 24	~90 – 93% quartz + 7 – 10% high-performance resin; not self-burning; toxic byproducts when burned; major hazard is respirable crystalline silica dust / 石英約佔 90 – 93%，樹脂 7 – 10%；不自燃；燃燒副產物毒性更強；主要風險為加工過程釋放之可吸入結晶二氧化矽粉塵
Ceramic Tile / 瓷磚（陶瓷瓦）	0.5 – 0.7	~40	~2000	20 – 28	High-temp kiln (>1000 °C) / 高溫窯燒
Cement Plaster (Render) / 水泥砂漿抹面	0.6 – 0.9	~42	~2100	25 – 38	Cement drives emissions / 水泥含量驅動高排放
Float Glass (Exterior Glazing) / 平板玻璃（外牆玻璃）	1.0 – 1.3	~50	~2500	50 – 65	Energy-intensive melting / 高耗能熔爐生產

Material / 材料	PCF (kg CO_2e/kg)	Mass (kg)	Density (kg/m^3)	PCF per 1 m^2 (kg CO_2e)	Notes / 註解
Steel Plate / 鋼板	1.8 – 2.5	~157	~7850	280 – 390	Very energy-intensive smelting; very high PCF / 極高能耗冶煉，碳足跡極高
Resin-based Artificial Stone / 人造石（樹脂為主）	2.0 – 3.5	~36	~1800	70 – 125	~90 – 95% resin; highly flammable; continues burning; thick toxic smoke (CO, VOCs, styrene) / 樹脂含量約 90 – 95%；極易燃燒且持續助燃；產生大量有毒濃煙（CO、VOC、苯乙烯等）
Paint (Exterior Acrylic, 0.2 mm film) / 外牆塗料（壓克力漆，0.2 mm 厚）	2.5 – 4.0	~0.24	~1200	0.6 – 1.0*	Thin layer, needs repainting every 10 – 15 years / 薄層塗佈；需每 10 – 15 年重塗一次

📌 Notes / 註解

1. **Paint / 塗料**: The lowest per-m^2 PCF value is only due to extremely thin coating; exterior walls require repainting every 10 – 15 years, which significantly increases lifetime emissions.
   塗料：每 m^2 排放值最低僅因塗層極薄；建築外牆需每 10 – 15 年重塗一次，若計入整個壽命週期，總排放顯著上升。
2. **Density / 密度**: Physical property of the material, mass per unit volume. Example: granite ≈ 2600 kg/m^3; steel ≈ 7850 kg/m^3.
   密度：材料本身的物理性質，即單位體積的質量。例如：花崗岩 ≈ 2600 kg/m^3；鋼材 ≈ 7850 kg/m^3。
3. **Mass / 質量**: Formula = Density × Thickness × Area. For 1 m^2 × 0.02 m: 0.02 m^3 × 2600 = 52 kg (granite).
   質量計算公式 = Density × Thickness × Area。以 1 m^2 × 0.02 m 厚度為例：0.02 m^3 × 2600 = 52 kg（花崗岩）。
4. **PCF per m^2 / 每平方公尺碳足跡**: Formula = Mass × PCF per kg. Example: granite 52 × 0.20 ≈ 10 kg CO_2e/m^2.
   每平方公尺碳足跡公式 = Mass × PCF per kg。例如：花崗岩 52 × 0.20 ≈ 10 kg CO_2e/m^2。

5. **Wood, artificial wood, paint / 木材、人造木材與塗料**: Applying 1 m^2 × 2 cm is unrealistic; very different strength and lifetime. PCF per kg is a fairer basis for comparison.
   天然與人造木材及塗料在應用 1 m^2 × 2 cm 時，其壽命與強度差異極大。因此，以 PCF 每公斤作為比較基準更為合理。
6. **Engineered Quartz / 人造石英**: Resin content is low, but higher-performance resin emits more toxic byproducts; main hazard is respirable crystalline silica dust released in fabrication, linked to silicosis and 2024 nationwide ban in Australia.
   人造石英：樹脂比例低，但所使用的強化樹脂燃燒副產物毒性更高；主要危害為乾式切割、研磨與拋光時釋放之結晶二氧化矽超細粉塵，已在澳洲引發矽肺並導致 2024 年全國禁用。
7. **Resin-based Artificial Stone / 人造石（樹脂為主）**: Resin proportion very high; burns easily and continues burning; produces large amounts of toxic smoke (CO, VOCs, styrene).
   人造石（樹脂為主）：樹脂含量極高，燃燒時持續助燃並釋放大量有毒濃煙，對火災安全構成重大風險。
8. **Natural Stone / 天然石材**: Non-combustible, produces no toxic smoke; in fire, breaks into coarse fragments that mostly fall to the ground, with minimal airborne risk.
   天然石材：不燃燒、不產生有毒煙霧；火災中僅碎裂成粗顆粒粉塵，主要落於地面，空氣懸浮風險極低。
9. **Steel as real façade products**: Corrugated sheet (1 mm) has a PCF of **14 – 20 kg CO_2e/m^2**; cassette panel (3 mm) has **42 – 59 kg CO_2e/m^2**. These values are far lower than the 2 cm plate shown in the table, and they position steel realistically between cement plaster (25 – 38) and resin-based artificial stone (70 – 125).
   鋼材在實際外牆應用：鐵皮浪板（1 mm）每平方公尺碳足跡為 **14 – 20 kg CO_2e/m^2**；金屬飾板（3 mm）為 **42 – 59 kg CO_2e/m^2**。這些數值遠低於表中 2 cm 厚鋼板的 280 – 390，並合理地落在水泥抹面（25 – 38）與樹脂為主的人造石（70 – 125）之間。

4.🕮 Use Phase & Durability / 使用階段與耐久性

- **Natural stone**: Very high durability and weather resistance, requires little maintenance; surfaces can be refinished (repolished).
- **Ceramic tiles**: Durable, but joints and waterproofing layers need maintenance; damaged tiles are difficult to reuse.
- **Cement plaster**: Prone to weathering and cracking, higher maintenance frequency.
- **Wood / Artificial wood**: Requires protective coatings and regular maintenance outdoors; durability strongly affected by climate.
- **Glass and steel**: Strong functional use but high energy and maintenance/cleaning costs.

- **天然石材**：極高耐久性與耐候性，低維護；表面可再加工（翻新、再拋光）。
- **陶瓷磚**：耐磨，但勾縫與防水層需維護；破損難以整片再用。
- **水泥抹面**：易風化龜裂，維護頻率較高。
- **木材/人造木材**：外牆需保護塗層與定期維護，耐久性受氣候影響。
- **玻璃與鋼材**：功能性強但能耗與維護清潔成本高。

5. End-of-Life & Reuse / 拆除、廢棄與再利用

- **Natural stone (Reuse)**: When mechanically fixed (dry-hanging, anchors/bolts), panels can be uninstalled → metal fixings removed → cut/resized → reused. The material remains raw stone without chemical treatment.
    - Metal fixings cannot be reused as-is, but can be recycled (potential substitution benefit at stage D).
    - In practice, this enables **near-zero construction waste**, with C1 – C4 emissions much lower and D gaining recycling benefits.
- **Artificial/Composite materials**: Usually mixtures (resins, binders, fibers). After removal, they cannot be separated back into raw materials. Disposal often means **downcycling** or **energy recovery**.
    - C1 – C4 emissions and handling losses are often underestimated or ignored, and D stage substitution benefits are limited.
- **Fair comparison suggestion**: Besides A1 – A3, it is recommended to quantify **reuse rate (%)**, **metal recycling rate (%)**, and **transport distance after demolition**, and present a **sensitivity analysis** including C and D stages.

- **天然石材（重用）**：以機械固定（乾掛、鑄件/螺栓）者，可拆除 → 去除金屬件 → 切割調整尺寸 → 再用；材料仍為原生石材，不需還原或化學處理。
    - 金屬固定件不可原件重用，但可回收冶煉（D 階段潛在替代效益）。
    - 實務上可達 **近零建廢** 場景，C1 – C4 排放大幅降低，D 階段獲得回收效益。
- **人工/複合材料（難以回復原料態）**：多為混合材（樹脂、黏結劑、纖維等），拆除後難以分離回到初始原料狀態，常以 **降級回收** 或 **能源回收** 處理。
    - C1 – C4 排放與處理損失常被 **低估或忽視**，D 階段之替代效益受限。
- **公平比較建議**：在呈現 A1 – A3 主表外，另以情境化方式定量 **可重用率（%）**、**金屬件回收率（%）**、**拆除與運輸距離**，並在附錄給出 **C 與 D 的加總敏感度分析**。

6. ✓ Key Messages / 關鍵訊息

1. Under the same specification (1 m² × 2 cm, A1 – A3), **natural stone has a lower PCF than ceramic tile and cement plaster**.
2. For stone, **quarrying is the dominant emission stage**, while cutting and polishing contribute relatively less.
3. **Reusability and recyclability** (stone panels + metal fixings) give natural stone strong advantages at C/D stages, enabling **near-zero construction waste**.
4. **Artificial/composite materials** cannot revert to raw state, resulting in hidden or underestimated burdens at end-of-life.
5. Public reports should always state **functional unit, boundaries, data sources, and versions** (ICE v3.0, Ecoinvent v3.9, EN 15804 EPD, JEMAI) to avoid miscomparisons.

1. **同規格（1 m²×2 cm，A1 – A3）比較**時，天然石材碳足跡低於瓷磚與水泥抹面。
2. 天然石材以 **開採端為主要排放來源**；切割與拋光之相對貢獻較小。
3. **可拆卸重用**與**金屬件回收**使天然石材在 C/D 階段具顯著優勢，可接近 **零建廢**。
4. **人工/複合建材**因難以回復原料態，在 C1 – C4/D 階段常產生隱含或未充分計入的排放。
5. 公開文件應明確列示 **功能單位、邊界、資料來源與版本**（ICE v3.0、Ecoinvent v3.9、EN 15804 EPD、JEMAI），避免跨來源/跨邊界誤比。

7. Conclusion / 結論

Natural stone combines low A1 – A3 PCF, high durability, and reusability. To compare fairly, PCF of building materials should consider the life time of each material and the PCF during and after uninstallation. Although this may not be necessary at the planning stage, it becomes critical during uninstallation and renewal stages, which can stop or slow down development and the economy. / 天然石材兼具低初期碳足跡、高耐久與可重用之優勢。為了公平比較，建材的碳足跡應考量其壽命，以及拆除過程與拆除後的碳足跡。雖然在規劃階段未必重要，但在拆除與更新階段則至關重要，因為這可能會阻礙或延緩發展與經濟。

8. Acknowledgement / 致謝

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- ## 9.📎 Appendix – References / 附錄 – 參考文獻

- ISO 14067: Greenhouse gases — Carbon footprint of products — Requirements and guidelines
  🔗 ISO 14067 Standard https://www.iso.org/standard/71206.html
  (Official ISO standard; purchase required. Used in this report as the methodological framework, not for direct figures.)
  國際標準化組織 ISO 14067（產品碳足跡規範）
  👉 官方標準，需付費購買。本報告引用其方法框架，非直接數據來源。
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- EN 15804+A2: Sustainability of construction works — Environmental product declarations — Core rules for construction products
  🔗 CEN EN 15804+A2
  https://standards.cen.eu/dyn/www/f?p=CENWEB:105::RESET::::
  (European construction product EPD framework; purchase required. Basis for all European EPDs cited here.)
  歐洲標準 EN 15804+A2（建材環境產品宣告核心規範）
  👉 官方歐洲標準，需付費購買。為本報告引用之歐洲建材 EPD 的依據。
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- ICE Database (latest available release) v3.0, University of Bath (UK) — Embodied carbon factors for construction materials
  🔗 ICE Database Download https://circularecology.com/embodied-carbon-footprint-database.html *(Public and free. Figures for stone, brick, concrete, steel taken from ICE v3.0 Excel, Table 1.)*
  英國巴斯大學 ICE Database v3.0（建材隱含碳資料庫）
  👉 公開免費。本報告所列石材、磚、混凝土、鋼材數據來自 ICE v3.0 Excel 表格。
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- Ecoinvent v3.10 (Switzerland) — Life cycle inventory database
  🔗 Ecoinvent Database https://ecoinvent.org/ecoinvent-v3-10
  (Subscription or academic license required. Figures for stone, cement, glass, and metals are from global average datasets.)
  瑞士 Ecoinvent v3.10（全球生命週期清單資料庫）
  👉 需訂閱或學術授權。本報告所列石材、水泥、玻璃、金屬等數據來自其全球平均資料集。
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- Confindustria Ceramica (Italy) — Ceramic tile Environmental Product Declarations (EN 15804)

🔗 Ceramic Tile EPDs https://www.confindustriaceramica.it/site/en/home/epd.html
(Free PDFs, registration may be required. Used for ceramic tile PCF values, EN 15804-compliant.)
義大利陶瓷工業聯盟（Confindustria Ceramica） – 瓷磚 EPD（依 EN 15804 標準）
👉 免費 PDF，部分需註冊。本報告所列瓷磚碳足跡數據引用自其 EPD。

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- European Natural Stone EPDs (via IBU EPD Online Portal, Germany)
🔗 Natural Stone EPDs: https://epd-online.com
(Free access to verified EPD documents for marble, granite, sandstone under EN 15804.)
歐洲天然石材 EPD（德國 IBU EPD 線上平台）
👉 免費取得，提供大理石、花崗岩、砂岩等依 EN 15804 標準的 EPD 文件。

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- Japan Environmental Management Association for Industry (JEMAI) — CFP/EPD system
🔗 JEMAI CFP/EPD https://www.jemai.or.jp/english/
(Entries for stone, cement, ceramics, glass, and metals. Requires registration; available in English and Japanese.)
日本產業環境管理協會（JEMAI） – CFP/EPD 系統
👉 涵蓋石材、水泥、陶瓷、玻璃、金屬等。需註冊，提供日文與英文資料。

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- Architecture & Building Research Institute, Taiwan — Green Building Material Label
🔗 ABRI Taiwan Green Label https://www.abri.gov.tw/
(Official embodied carbon factors for Taiwan-certified green building materials. Public access.)
台灣建築研究所 – 綠建材標章
👉 公開數據，提供台灣認證建材的碳足跡因子。

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- UL Environment – Quartz Surfaces Environmental Product Declarations (EPDs)
🔗 UL Spot – Quartz Surfaces EPDs https://spot.ul.com/main-app/products/search?searchType=EPD&query=quartz%20surface
(Official UL certification database for Environmental Product Declarations)
Official Environmental Product Declarations for engineered quartz surfaces, including

A1 – A3 cradle-to-gate carbon footprint data.

👉 UL 環境認證之石英表面環保產品宣告，涵蓋 A1 – A3 階段碳足跡數據。

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- OSHA & NIOSH – Hazard Alert (2015)

  🔗 Worker Exposure to Silica during Countertop Manufacturing, Finishing, and Installation (OSHA 3768)

  https://www.osha.gov/sites/default/files/publications/OSHA3768.pdf (U.S. Occupational Safety and Health Administration & National Institute for Occupational Safety and Health)

  Official hazard alert linking engineered stone fabrication to respirable crystalline silica exposure and silicosis risk.

  👉 美國職安署與職安衛生研究所聯合發表的官方警示，指出人造石英製作過程中結晶二氧化矽暴露與矽肺風險。

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- Safe Work Australia – National Prohibition on Engineered Stone (2024)

  🔗 Engineered Stone Ban – Safe Work Australia

  https://www.safeworkaustralia.gov.au/engineered-stone-ban

  (Australian Government official site)

  Australia's official prohibition on engineered stone nationwide (effective 1 July 2024) due to incurable silicosis cases among workers.

  👉 澳洲政府官方決策，自 2024 年 7 月 1 日起全面禁止使用人造石英，原因為矽肺病例無法治癒。

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- Safety Data Sheets (SDS) – Unsaturated Polyester & Epoxy Resins

  🔗 Dow Chemical SDS Finder

  https://www.dow.com/en-us/support/sds-finder.html

  (Global chemical company SDS database)

  Standard reference for combustion properties and toxic byproducts of resins commonly used in artificial stone production.

  👉 樹脂（不飽和聚酯樹脂、環氧樹脂）之安全資料表，揭示人造石材使用樹脂之燃燒特性與有毒副產物。