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QUANTIFYING EMBODIED CARBON EXPENDITURE IN GREEN MAINTENANCE OF HERITAGE BUILDINGS: A CASE STUDY OF MARSEILLE CLAY ROOF TILES REPAIR

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Abstract

Green Maintenance (GM) inculcates sustainable planning and development of heritage buildings and the historic environment. It promotes practices in line with the Conference of the Parties of the United Nations Convention on Climate Change (UNFCCC) or COP and Sustainable Development Goals (SDGs) aspirations, thus underpinning decision-making in low-carbon repair options and supporting environmentally focused conservation. This paper aims to quantify embodied carbon expenditure in GM based on a carbon Life Cycle Assessment (LCA) and Environmental Maintenance Impact (EMI) evaluation in the conservation of a selected heritage building in the case of Marseille clay roof tiles repair. The research found that Marseille-Mornier tiles repair of Bangunan Sultan Abdul Samad contributed to 58,116.84 kgCO₂e of the overall total EMI. The research results demonstrated that adopting carbon LCA and EMI enhanced understanding of the complex relationship between Marseille clay roof tile repair and its environmental impact and performance. More importantly, the adopted carbon LCA and EMI could be appreciated regarding CO₂ emissions reduction and interdisciplinary heritage building conservation establishment.

Keywords: Embodied carbon expenditure, Green Maintenance (GM), Marseille clay roof tiles, Life Cycle Assessment (LCA), Environmental Maintenance Impact (EMI), low-carbon repair

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INTRODUCTION

Maintenance is all practical and technical measures to keep heritage buildings at a standard that permits enjoyment of their cultural significance and resources without damage (Burra Charter, 2013). Moreover, it is a self-correcting balance that puts heritage buildings' structure and elements into their original condition within the heritage preservation philosophical framework (British Standards Institution, 1998). Importantly, this is aligned with the Green Maintenance (GM) concept and methodology.

GM is gaining popularity in the sustainability domain, as evidenced by the growing trend in research and published works. GM is well known for its support of good maintenance and low-carbon repair strategy (Kayan et al., 2024) and sustainable planning and development of heritage buildings and the historic environment (Nursaniah et al., 2023; Mari et al., 2024). Moreover, GM is recognised for reducing embodied carbon expenditure from repair (Sari et al., 2023). Practically, GM is aligned with the aspirations of the 27th Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC) or Conference of the Parties 27 (COP 27) (2022). In terms of environmental sustainability of heritage buildings, GM also embraces the U.N.'s Sustainable Development Goal 13 (SDG13), i.e. to combat the adverse impact of climate change, as well as Sustainable Development Goal 11 (SDG11). Despite this, efforts to quantify embodied carbon expenditure from building's elemental repair in heritage building conservation remained insufficient. For instance, there is a lack of attempts to quantify embodied carbon expenditure for Marseille clay roof tile repair in terms of life-cycle environmental performance. Likewise, quantification of embodied carbon expenditure for roof covering materials used in a tropical country like Malaysia is still lacking. Moreover, previous research largely focuses on the preservation of roof structures and materials (Hassan and Harun, 2013), assessment of production quality of roof covering (Abdullah, 2014) and modern application of roof materials (Nouri et al., 2021).

In response, this paper aims to show that quantifying embodied carbon expenditure in GM for roof elemental repair (in this case, Marseille clay roof tiles) via the application of a carbon Life Cycle Assessment (LCA) and Environmental Maintenance Impact (EMI) evaluation enables the achievement of low-carbon repair in heritage building conservation. Significantly, this could be appreciated in CO₂ emissions reduction and interdisciplinary heritage building conservation establishment.

LITERATURE REVIEW

This section gives an insight into an overview, focuses on historical background, traditional manufacturing processes, the profile, and common pathological and technical issues of Marseille clay roof tiles. The association and quantification

of embodied carbon expenditure in the context of a sustainable repair approach, as well as recycling and salvaging options, aspired to through Green Maintenance, are also elaborated. Traditionally, the accepted conceptual model of sustainability is overlaid with three factors that influence the maintenance of heritage buildings: environment, cost, and philosophy. Those interventions that intersect with all three domains would potentially be considered as being the most sustainable concept and methodology for maintenance, i.e. “Green Maintenance” (GM).

The frequency of maintenance interventions (such as this case repair to Marseille clay roof tiles) will eventually affect the level of CO₂ emissions. In most cases, the best repair techniques are twinned with sustainable low-carbon repair materials. Note that GM is parallel with the generally accepted model for the evaluation of ‘sustainable’ or ‘green’ maintenance interventions (Kayan, 2017; Sari et al., 2023). Significantly, this research associates maintenance interventions, e.g. repair to Marseille clay roof tiles, with a carbon LCA and EMI assessment of GM. The unifying concept and methodology of GM can be seen as a tool for promoting good maintenance interventions in terms of embodied carbon expenditure (CO₂ emissions) with minimal environmental impact, as well as promoting a sustainable repair approach for heritage buildings. This will become a key performance indicator in the good repair impact strategies.

Marseille Clay Roof Tiles: An Overview

Historical Background

Historically, Marseille clay roof tiles were popular worldwide. The earliest produced Marseille clay roof tiles of the French Gilardoni variety have been extensively used in Europe since the 1880s (ACAHUCH, 2025). In Australia, Saccoman of St Henry Marseille clay roof tiles were imported as early as the 1860s, and by the late 1880s began to appear on local buildings such as Alexander McCracken’s House, and at ‘North Park’ (later ‘Woodland’s’) at Essendon, Melbourne, in 1889) (Australasian Builder and Contractor’s News Publishing Co., 1889). Remarkably, the initial production and usage of Marseille clay roof tiles globally is widespread; e.g. New Zealand (1900s), India (1880s), South America (1890s), and Singapore (1920s) (ACAHUCH, 2025). In Malaysia, the earliest usage of Marseille clay roof tiles was in the local heritage buildings of diverse functions and typologies. As early as the 1920s (similar to Singapore) they were frequently used in colonial buildings in Pulau Pinang (Ibrahim-Bell, 2019). Moreover, research by Ibrahim-Bell (2019) found that Saccoman Freres of St Henri Marseille tiles (commonly known as 19th-century French tiles) were used in historic bungalows and cottages in Fraser’s Hill, Pahang. Characteristically, as shown in Figure 1, the flat interlocking Saccoman Freres of St Henri Marseille tiles are produced by two deep vertical grooves on the surface

that facilitate drainage, printed with the manufacturer's crest and batch on the back, and finished with holes at the top for nailing (usually two holes, with a dab of cement for added security, sometimes the tiles have a small knob with a hole through which wire can be inserted to secure the tile to the roof battens) (Grimmer & Williams, 1993). Despite the long historical background and usage in heritage buildings, attempts to quantify embodied carbon expenditure for Marseille clay roof tile repair in terms of life-cycle environmental performance remain lacking.

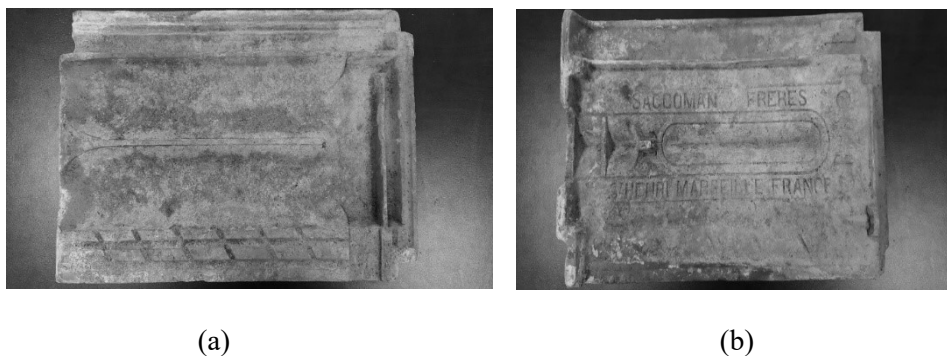


Figure 1: Saccoman Freres, St Henri, Marseille, France tile pattern:
(a) upper side, and (b) underside
Source: Authors (2025)

Traditional Manufacturing Processes

The traditional manufacturing processes of Marseille clay roof tiles involved four stages: first, the extraction and resourcing of clay; second, the main production/manufacturing; third, storage of the final product; and finally, distribution (transportation/delivery to the building site) (Figure 2).

The Profile

Marseille clay roof tiles have been around for centuries, proving their long-lasting durability, thermal conductivity and elegant attributes. The tiles are long-lasting, durable, watertight, and have good thermal conductivity (ACAHUCH, 2025). The tiles have an elegant look, are available in a wide variety of sizes, shapes, colours, profiles, patterns, and textures (Grimmer & Williams, 1993).

Common Pathological and Technical Issues

Despite its wide usage and application, Marseille clay roof tiles used in heritage buildings are affected by pathological and technical issues. Common pathological issues include weathering effects, pollution, microorganism attacks, overflowing rainwater and roof leakage. Technically, the tiles require special care and precaution, thus, causing difficult cleaning and treatment processes and complicated repair work procedures (Grimmer & Williams, 1993).

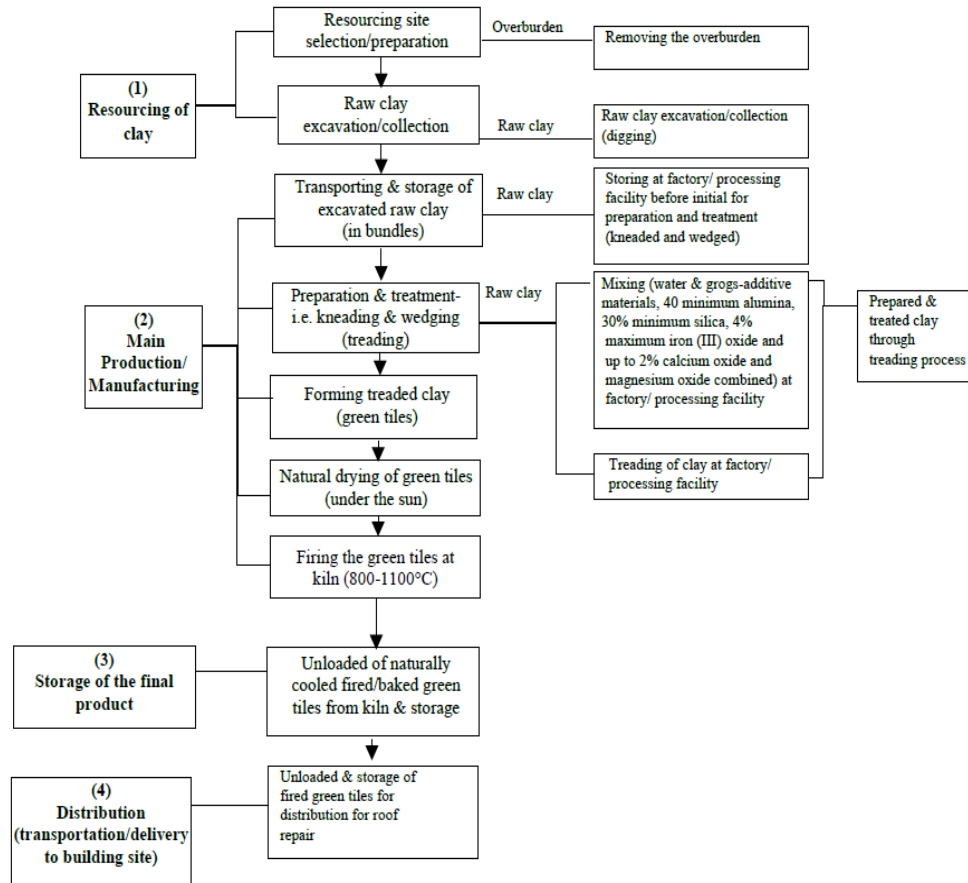


Figure 2: Traditional manufacturing processes of Marseille clay roof tiles
 Source: Authors (2025)

Repair Impact on Embodied Carbon Expenditure and Sustainable Repair Approach

Roof repair options and their respective embodied carbon expenditure are usually determined by building design and forms, the repaired roof surface area, and the tiles used (Kayan & Ashraf, 2023). Considering the wide usage of Marseille clay roof tile in heritage buildings, the influences of repair in terms of the building's life-cycle environmental performances would be cumulatively significant. On the other hand, Marseille clay roof tiles are also known for their ability to sequester carbon, i.e., have better environmental credentials and performance compared to modern roof covering materials such as composites, concrete and zinc. Other roof repair approaches using modern tile materials that practitioners

might adopt are beyond the scope of this research's carbon LCA and EMI evaluation.

Recycling and Salvaging Options from A Low-Carbon Repair Perspective

Ideally, recycling or salvaging options may appear to be a good solution to the shortage of historic and traditional Marseille clay roof tiles, thus enabling low-carbon repair. However, the additional processes of sorting, cleaning and disposal of the tiles will cumulatively contribute to the additional embodied carbon expenditure.

RESEARCH METHODOLOGY

Case Study: Bangunan Sultan Abdul Samad

Bangunan Sultan Abdul Samad (Figure 3) inherited late 19th-century Indo-Saracenic, Neo-Mughal and Moorish styles, elaborated with pitched-Marseille clay roof tiles. The building was declared a National Heritage on 24 December 2008, under the National Heritage Act (Act 645) Malaysia, Section 67 (2)(a), i.e., a building with historical importance, association with or relationship to Malaysian history (Malaysia, 2006). The building's background and technical specifications for the Marseille roof tiles and common defects are described in Table 1. In 2019, a major repair was undertaken to the damaged roofing structure and covering materials using locally sourced Marseille-Monier clay roof tiles. In the case of this paper, the defective or damaged Marseille-Monier clay roof tiles are replaced with identical specification and similar materials to attain their authenticity based on repair work procedures by Jabatan Warisan Negara, Malaysia (JWN).

Repair Work Procedures

Due to the National Heritage status of Bangunan Sultan Abdul Samad, the repairing strategy and procedures for Marseille-Monier clay roof tiles are specified in Section 3.1 of the 2017 "Heritage Building Conservation Guidelines" issued by Jabatan Warisan Negara, Malaysia (JWN). The guidelines stated (i) adoption of approved methods of investigating and identifying the tile's profile such as originality and condition (including original finishes), (ii) rehabilitative and protective treatment (to avoid damage during repair), (iii) re-use of salvaged materials and similar materials in terms of type, appearance, colour, texture, etc., and (iv) usage of identical materials and original placement layout and technique. The repair work procedures of Marseille-Monier clay roof tiles for the case study building are further explained in Figure 4.



Figure 3: Bangunan Sultan Abdul Samad (case study)

Source: Authors (2025)

Table 1: Case study's background, roof tiles specification and defects

Location	Year Built	Construction Method	Current Function	Building Data & Characteristics	Roof Tiles Technical Specifications	Roof Tiles Common Defects
Kuala Lumpur, Malaysia	1894 – 1897, 126 years old	Two storeys, red bricks, with a pitched tiled roof	Public institution	- Known as the 'Federal Secretariat' (1897) - Named after Sultan Abdul Samad (1857-1898) - Designed by A.C. Norman, assisted by R.A.J. Bidwell in a Classical Renaissance style - Reworked by Bidwell, commissioned by C. E. Spooner - Building fixtures by A.B. Hubback	19th-century Marseille Mornier brand/type - Interlocking - Variable gauge-great flexibility - Exclusive "Bee" mark - Natural colour - Number of tiles per m²: 13.5 - Dimensions (cm): 42 x 26 - Batten gauge/spacing (cm): 32 to 36 +/- 0.3 between each tile - Weight (kg): ≈ 3.7 - Laid with straight joints right to left - Minimum roof pitch: 30% (16°70')	- Dirt-stained - Fungus-infested - Discoloured - Faded/dulled - Cracks - Broken - Holes - Misalignment - Displacement

Source: Authors (2025)

Carbon LCA and EMI Evaluation

The evaluation was undertaken to evaluate embodied carbon expenditure from the repair of Marseille clay roof tiles (in the form of CO₂ emissions) using the equation in Table 2 and a set of unit processes and workflows in Figure 4. Conceptually, Figure 4 demonstrates on how calculation procedures within cradle-to-site boundary of LCA in this paper were underpinned by EMI evaluation and correlated with the respective longevity, *l* and frequency of repair,

f_x (as in equation No. 3). Note that, f_x is frequency of Marseille clay roof tiles repair options within arbitrary period, while $\sum ECE_{cradle-to-site}$ is overall total embodied carbon expenditure from cradle-to-site of LCA.

Table 2: Equation adopted in integrated carbon LCA and EMI

Equation	Output	Equation Formulae	Remarks
(1)	Overall total embodied carbon expenditure from cradle-to-site	$\sum ECE_{cradle-to-site}$ $= \sum ECE_{cradle}$ $- to - gate$ $+ \sum ECE_{gate-to-site}$	Within Cradle-to-site boundary of LCA
(2)	Total EMI	where; $\sum ECE_{cradle-to-site} = \text{Overall total of Embodied Carbon Expenditure (kgCO}_2\text{e/kg)}$ $\sum_{t=1}^n EMI_{cradle-to-site}_{t_n} = EMI_{cradle}$ $- to - site_{t_1}$ $+ ... EMI_{cradle-to-site}_{t_n}$ where; t_n = longevity of Marseille clay roof tiles repair $EMI_{cradle-to-site}$ = total EMI within the cradle-to-site boundary of LCA [generated from Equation No. (1)]	Within selected arbitrary years of maintenance profile periods, the value entered in Equation (2) will determine the overall total EMI
(3)	Frequency of Marseille clay roof tile repair	$f_x = \frac{x_{years}}{l}$ where; l = longevity of Marseille clay roof tiles repair x_{years} = arbitrary period (years) of Marseille clay roof tiles repair options f_x = frequency of Marseille clay roof tiles repair options within an arbitrary period	The f_x can be calculated using an arbitrary period (in this paper is 100 years, divided by the estimated longevity of repair, l of 50 (supplier's data))
(4)	Overall total EMI within an arbitrary period	$\sum EMI_{years} = \sum ECE_{cradle}$ $- to - site \times f_x$	The overall total EMI within the arbitrary period (in this paper is 100 years)

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Equation	Output	Equation Formulae	Remarks
		where; f_x = frequency of Marseille clay roof tile repair within an arbitrary period $\sum EMI_{years}$ = Overall total EMI (kgCO ₂ e) within an arbitrary period	

Source: Authors (2025)

It should be noted that the topics and Green Maintenance concept and methodology adopted in this research have been applied in previous studies such as Kayan's 2017 "Green Maintenance for Heritage Buildings: Paint Repair Appraisal" (Kayan, 2017) and Kayan & Ashraf's 2023 "Evaluating the Environmental Maintenance Impact (EMI): A Carbon Life Cycle Assessment (LCA) of the Singgora Roof Tiles Repair in Heritage Buildings" (Kayan & Ashraf, 2023). Nevertheless, it has to be pointed out that this paper's study has established its significance and novelty. Even though both the previous studies were undertaken in the same tropical region, the selected Bangunan Sultan Abdul Samad and the investigated Marseille-Monier clay roof tiles in this research were different in terms of building orientation, exposure to local weathering agents, and rate of degradation. Comparatively, the earlier study by Kayan (2017) focuses on paint repair on the roof surface and its covering materials, while the work by Kayan & Ashraf (2023) researched Singgora roof tile repair.

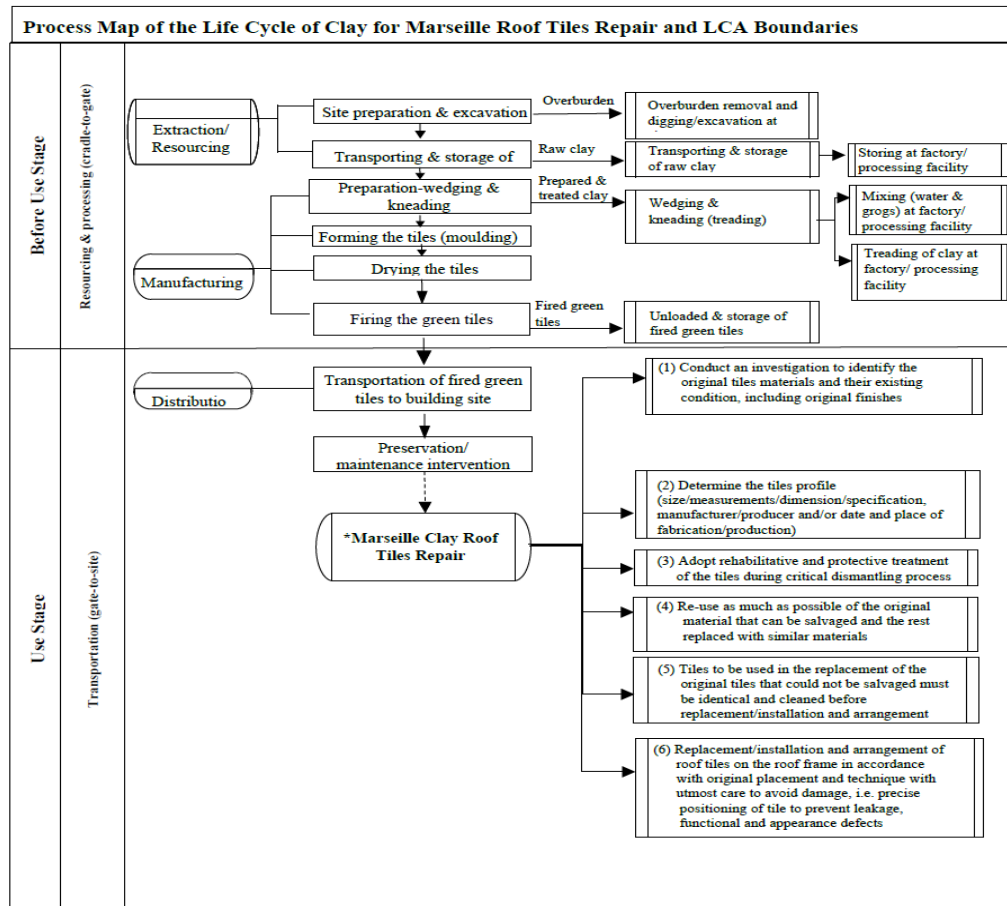


Figure 4: Process map of the life cycle of clay for Marseille clay roof tiles repair

Source: Authors (2025)

Moreover, the embodied carbon coefficient value $\frac{ecc_{kgCO_2e}}{kgm^2}$ of 0.48 kgCO₂e/kg of common clay materials of Marseille clay roof tiles generated in CIDB's Embodied Carbon Inventory Data for Construction Materials 2021 was adopted in this research as opposed to 0.24 kgCO₂e/kg in earlier work by Kayan & Ashraf (2023). This is to better represent the embodied carbon coefficient value of common clay materials for Marseille clay roof tiles in the local context of Malaysia.

The adopted carbon LCA and EMI in this research utilised data from the United Kingdom (UK) and Malaysia (mainly due to similar power generation and modes of transportation used). Within the cradle-to-gate boundary of LCA, an embodied carbon coefficient value is derived from the Construction Industry

Development Board (CIDB) Malaysia's Embodied Carbon Inventory Data for Construction Materials (2021) and UK Government GHG Conversion Factors for Company Reporting (Department for Energy Security & Net Zero & Department for Environment, Food & Rural Affairs, 2024).

ANALYSIS AND DISCUSSION

Total Mass Kg of Repair Materials and Approximate Repaired Roof Surface Area

Table 3 shows the mass, m_{kg} (kg), repaired roof area, A_{m2} (m^2) and mass kg/m^2 of Marseille clay roof tiles repair materials for Bangunan Sultan Abdul Samad. It can be established that the total mass kg of Marseille clay roof tiles repair materials for the building relied upon different numbers of replaced/re-installed tiles on the repaired roof surface area (in m^2).

Functional Units of Embodied Carbon Per m^2 : Total $kgCO_2e/kg/m^2$

Table 4 shows functional units of embodied carbon per m^2 ($kgCO_2e/kg/m^2$), undertaken on 1 m^2 of Bangunan Sultan Abdul Samad's roof surface repaired area using Marseille clay roof tiles. It can be concluded that the functional units of this research generated within cradle-to-site carbon LCA are highly influenced by the total mass of tiles m_{kg} (kg) for repair, transportation distance to the building site, d_{km} (km), and embodied carbon coefficient, $ecc_{kgCO_2e/kg\ m^2}$ and carbon emission

factors, $ef_{\frac{kgCO_2e}{kg}}$.

Table 3: Total mass kg of Marseille clay roof tiles repair materials m_{kg} (kg) and total approximate repaired roof area A_{m2} (m^2) of Bangunan Sultan Abdul Samad

Tiles brand/type	Mass (kg)/tile (a)	No. of tiles/ m^2 (b)	Total mass (kg) tiles/ m^2 (c) = (a x b)	Total number of tiles for repair (d)	Total mass of tiles m_{kg} (kg) for repair (e) = (a x d)	Surface area (m^2)/tiles (f)	Total Approx. Repaired Roof Area A_{m2} (g) = (d) x (f)
Marseille-Monier	3.70	13.5	49.95	13,000	48,100.00	0.42 x 0.26 = 0.1092	1,419.60

Source: Authors (2025)

Table 4: Functional Units of Embodied Carbon Per m² (kgCO₂e/kg/m²) for Marseille roof tiles repair of Bangunan Sultan Abdul Samad

Life Cycle Assessment (LCA) Boundary						
Cradle-to-Gate			Gate-to-Site		Cradle-to-Site	
Total mass of tiles m_{kg} (kg) for repair	Transportation distance to building site d_{km} (km)	Embodied carbon coefficient $ecc_{kgCO_2e/kg\ m^2}$	kgCO ₂ e/kg/m ² (A)	Carbon emission factors $ef_{kgCO_2e/kg\ km}$	kgCO ₂ e/kg/m ² (B)	Total kgCO ₂ e/kg/m ² (A+B)
49.95	228.1	0.48	23.976	0.00054417	6.200	30.176

Source: Authors (2025)

Overall Total Embodied Carbon Expenditure (kgCO₂e)

Generated using Equation No. (1), the results in Table 5 show that the greater the number of replaced/ re-installed Marseille roof tiles during repair, the higher the overall total embodied carbon expenditure (kgCO₂e). It is discovered that a considerable 20.55% of the overall total embodied carbon expenditure for the transportation of Marseille clay roof tiles from Yong Peng, Johor, to the building site of Bangunan Sultan Abdul Samad in Kuala Lumpur.

Table 5. Overall Total Embodied Carbon Expenditure (kgCO₂e) within the cradle-to-site of Bangunan Sultan Abdul Samad

Life Cycle Assessment (LCA) Boundary								
Mass (kg)/ tile	Total number of tiles for repair	Total mass of tiles m_{kg} (kg) for repair	Transportation distance to building site, d_{km} (km)	Cradle-to-Gate		Gate-to-Site		Cradle-to-Site
				Embodied carbon coefficient $ecc_{kgCO_2e/kg\ m^2}$	Total embodied carbon expenditure (kgCO ₂ e) (A)	Carbon emission factors $ef_{kgCO_2e/kg\ km}$	Total embodied carbon expenditure (kgCO ₂ e) (B)	Overall total embodied carbon expenditure (kgCO ₂ e) (A+B)
3.70	13,000	48,100.00	228.1	0.48	23,088.000	0.00054417	5,970. 421	29,058.421

Source: Authors (2025)

Overall Total EMI (kgCO₂e) Within Arbitrary Period

Overall total $\sum EMI_{years}$ EMI (kgCO₂e) of Marseille roof tiles repair of Bangunan Sultan Abdul Samad, within an arbitrary period and cradle-to-site of LCA is the multiplication of functional units with their respective frequency of repair, f_x . Generated from Equation (2) and Equation (3), this can be expressed in Equation (4) (see Table 2). The overall total EMI was calculated within the selected arbitrary period of this research (in this case $f_x = 100$ years) and is shown in Table 7. For comparative purposes in this research, three different brands/types of tiles from the Marseille tiles family were selected. All of them were mainly

made from clay materials and were nearly identical to each other. The slight differences among the tiles are in terms of their mass (kg) and surface (m^2). Results show that Mornier 12-GCI generated the highest overall total EMI, followed by Marseille-Monier, and the lowest is by Marseille-Terreal. The lowest EMI by Marseille-Terreal is mainly due to the lowest mass kg/tile (3.6) and mass (kg) tiles/ m^2 (43.20), and total mass of tiles mkg (kg (46,800) (see Table 6). However, the heavier tiles will produce sturdier roofing material (ACAHUCH, 2025). Considering this, Marseille-Mornier and the Marseille-12 GCI should be more robust/durable materials as compared to Marseille-Terreal.

In the context of this research, the best Marseille clay roof tile brands/types for repair are not only viewed exclusively in terms of EMI. The most ideal tiles have to fulfil philosophical heritage conservation frameworks which include minimal intervention yet provide maximum preservation (Feilden & Jokilehto, 1993), like-for-like material replacement (Nursaniah et al., 2023; Mari et al., 2024), and respect for traditional craft skills (Kayan & Shafigh, 2022). The ideal tiles also comply with conservation guidelines, e.g. "Heritage Building Conservation Guidelines" by Jabatan Warisan Negara, Malaysia (JWN) and are aligned with the aspiration of UNFCCC or COPs as well as SDGs. Considering this, Marseille-Mornier used for repair on Bangunan Sultan Abdul Samad is the most ideal, both in terms of EMI and philosophical frameworks. There are many examples of replaced/re-installed Marseille clay roof tiles still functioning satisfactorily in well-maintained Malaysia heritage buildings of different designs, forms, types and functions, some of which are more than 100 years old: 18th-century British Colonial Buildings in Fraser's Hill and Cameron Highlands in Pahang (over 200 years old) (Bahauddin et al., 2010; Ibrahim-Bell, 2019), Crag Hotel and Woodside Cottage in Penang Hill, Pulau Pinang (130 and 222 years old respectively) (Raub et al., 2015); Stamp Museum (over 200 years old, built in the 17th century during Dutch occupation) (Sari et al., 2023) and The Hong Kong and Shanghai Banking Corporation (HSBC) building (111 years old, built in 1912) in Melaka; St Mary's Cathedral in Kuala Lumpur (129 years old, built in 1894); and the Sanitary Board Building in Taiping, Perak (131 years old, built in 1892) (Kayan & Shafigh, 2022).

The results in Table 6 show that as high as one-fifth of the overall total embodied carbon expenditure kgCO_2e for the transportation of Marseille clay roof tiles sourced from the Yong Peng, Johor, to the building site of Bangunan Sultan Abdul Samad in Kuala Lumpur. Comparative analysis for transportation of different brands/types of Marseille clay roof tiles from the same resourcing location, using a similar mode of transportation, demonstrates the same pattern of contribution upon the overall total embodied carbon expenditure. Thus, to lessen the transportation of material influence on the total embodied carbon expenditure in repair, it is practical to use locally sourced Marseille clay roof tiles.

Table 6: Comparative analysis of overall Total Embodied Carbon Expenditure (kgCO₂e) within cradle-to-site of different brands/types of Marseille clay roof tiles

								Cradle-to-Gate		Gate-to-Site		Cradle-to-Site
kg/ tile (a)	tiles /m ² (b)	kg tiles/m ² (c) = (a x b)	Total tiles (d)	Total <i>m_{kg}</i> (kg) for repair (e) = (a x d)	Surface area (m ²)/ tiles (f)	Total repaired roof area Am ² (g) = (d) x (f)	<i>d_{km}</i> (h)	<i>ecc_{kgCC}</i> <i>kg m</i> (i)	(kgCO ₂ e) (A)= e x i	<i>ef_{kgCO2e}</i> <i>kg</i> <i>km</i> (j)	kgCO ₂ e (B) = (e x h x j)	kgCO ₂ e (A+B)
Monier	3.7	13.5										
12 – GCI	4.1	11.9	48.8									
			13,000	53,300.00	0.119	1,544.4	228.1	0.48	25,584.0	0.00054417	6,615.872	32,199.87
Terreal	3.6	12.0	43.2									
				46,800.0	0.114	1,487.2			22,464.0		5,809.058	28, 273.05

Source: Authors (2025)

Table 7: Comparison of overall total EMI for Marseille clay roof tiles repair within the cradle-to-site of selected arbitrary period (100 years)

Brand/type	Overall total embodied carbon expenditure (kgCO ₂ e)	Frequency of roof tile repair within arbitrary periods, <i>f_x</i> (100 years)	Overall total EMI within cradle-to- site of selected arbitrary period (100 years) (kgCO ₂ e)
Monier	29,058.42		58, 116.84
12 – GCI	32,199.87	2	64,399.74
Terreal	28,273.05		56,546.10

Source: Authors (2025)

CONCLUSION

This research reveals that Marseille 12–GCI contributed to the highest overall total EMI of 64,399.74 kgCO₂e as compared to the lowest of 56,546.10 kgCO₂e for Marseille–Terreal. Marseille–Mornier tiles used in the case study of Bangunan Sultan Abdul Samad generated the second-highest EMI of 58,116.84 kgCO₂e. Marseille–Mornier tiles used to repair Bangunan Sultan Abdul Samad’s roofing are the most ideal as they embrace low-carbon repair materials options and fulfil the environmental sustainability and heritage building conservation philosophical frameworks. The research demonstrates that the adoption of integrated carbon LCA and EMI of GM enable the quantification of embodied carbon expenditure in the repair of Marseille clay roof tiles. Additionally, the research supports environmentally focused conservation and is aligned with sustainable planning and development of heritage buildings and the historic environment as per the aspirations of UNFCCC or COPs and SDGs. More importantly, carbon LCA and EMI of this research could be appreciated as a resource in CO₂ emissions

reduction and interdisciplinary heritage building conservation establishment, thus will be of value to both practitioners and researchers concerned with the low-carbon repair techniques and materials.

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DISCLOSURE STATEMENT

The authors report there are no competing interests to declare.

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