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ENVIRONMENTAL MAINTENANCE APPRAISAL ON LIME-BASED MORTAR REPAIR FOR HERITAGE BUILDINGS CONSERVATION

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Abstract

Gradually, sustainable maintenance in the heritage buildings conservation moving forward to achieve The Sustainable Development Goals (SDGs), 2030 Agenda. The aim of this paper is to determine sustainable lime-based mortar repair in heritage buildings conservation based on calculation procedures of Green Maintenance model within cradle-to-site boundaries of Life Cycle Assessment (LCA). The calculation appraises Environmental Maintenance Impact (EMI) of selected case studies. This underpins informed decision-making in low carbon repair options in heritage buildings conservation. EMI appraisal of Green Maintenance Model in this paper is not confined to heritage buildings and can be applied to any building of different technologies and materiality. Moreover, EMI appraisal in this paper may enhance understanding of the relationship between lime-based mortar repair and their environmental performance. Significantly, this paper establishes interdisciplinary conservation strategies for heritage buildings located at UNESCO World Heritage Site (WHS).

Keywords: Environmental Maintenance Impact (EMI), lime-based mortar repair, heritage buildings, Life Cycle Assessment (LCA), Green Maintenance, Sustainable Development Goals (SDGs)

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INTRODUCTION

An assessment of Heritage buildings, its history and conditions are essential in the study of buildings conservation. In Malaysia, the conservation procedure of heritage buildings follows the guidelines provided by the National Heritage Department Malaysia (NHDM) (Harun et al., 2020). Cultural heritage is an evolving resource that supports identity, memory, and a 'sense of place', and has a crucial role in achieving sustainable development. The Sustainable Development Goals (SDGs) adopted by the United Nations in 2015, is a plan of action for the economy, environment, and society, ICOMOS (Version, 2021).

Sustainable maintenance of heritage buildings means having a low impact on the environment by minimising the use of energy and releasing small amounts of embodied carbon. Embodied carbon refers to Carbon Dioxide (CO_2) emissions released through the process of extraction, manufacturing, and transportation of materials (Kayan et al., 2018). To evaluate the sustainable maintenance of heritage buildings in relation to the Green Maintenance Model, it is, therefore, necessary to understand the cumulative effect of routine maintenance operations in terms of environmental impact. The model places the priority on the selection of materials and repair technique options for maintenance in conservation based on the level of CO_2 emissions (Sari et al., 2023).

The most used materials over the ages have been lime-based mortar, that used with the natural stones, bricks, or manufactured blocks (Michelina Monaco & Marianna Aurilio, 2021). It is also associated with a considerable scale of production and corresponding CO_2 emissions (Forster et al., 2020). Today, about 35% of global energy consumption and related CO_2 emissions are caused by the construction sector including conservation of heritage buildings. The life cycle Analysis (LCA) is an evaluation tool capable of assessing the CO_2 emissions during the whole life cycle of a building (Angrisano et al., 2021). Therefore, to address sustainable repair in the heritage conservation, this attempts to identify sustainable lime-based mortar repair in terms of EMI. Importantly, this underpins informed decision-making in low carbon repair options as well as establishes interdisciplinary conservation strategies for heritage buildings conservation.

LIME-BASED MORTAR REPAIR APPRAISAL BASED ON GREEN MAINTENANCE MODEL: LCA APPROACH

The Green Maintenance Model applied to support the SDGs which call for preserving the cultural significance embedded in the fabric of heritage buildings while conserving other valuable resources (Kayan et al., 2018b). The concept takes philosophical factor, cost factor, and low environmental impact factor into evaluation. The repair techniques undertaken that included the three factors in figure 1 will be considered as being the most sustainable.

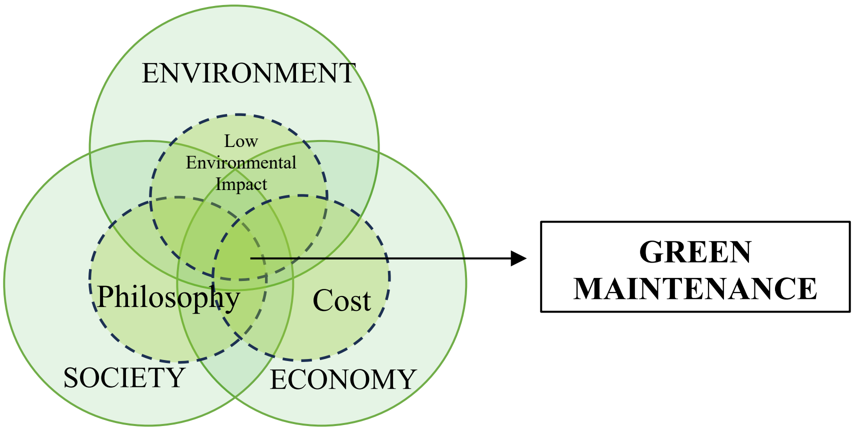

Figure 1: The Green Maintenance Model, Parameters for Evaluating the Maintenance Interventions for Heritage Buildings
Sources: Adopted by (Kayan et al., 2017)

The Green Maintenance methodology addresses the relationships between CO_2 emissions and repair technique options, which offers some insight into the choice of lime-based mortar repair for heritage buildings. As proved on the service figure 2;(Kayan et al., 2018), each intervention's lifespan (*l*) and embodied carbon expenditure (Ce) may be used to understand how they relate to one another.

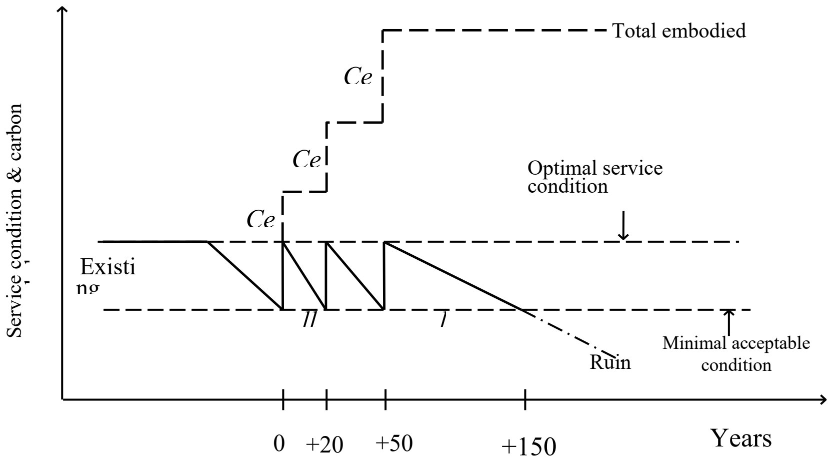

Figure 2: Relationship Between Longevity of Repair and Embodied Carbon Expenditure
Source: (Kayan et al., 2018)

Whenever the building is in ruin stage, the building must be repaired to achieve the minimal standard and optimal service condition. Along the way the process will contribute to the cumulative total embodied carbon. The less frequency of the repair the less total cumulative embodied carbon.

Lime-Based Mortar Repair for Conservation of Heritage Buildings Relationship with Carbon Dioxide (Co2) Emission

Lime-based mortar has been utilized for heritage buildings (Ventol et al., 2011) and applied in the conservation phase. It must be carefully studied regarding the best general techniques, in order to maximise the life span of the materials used to ensure the CO_2 emission is minimal during conservation (Grazzini *et al., 2022)*. The LCA was carried out in this paper to reduce the CO_2 emission caused by the operational, transportation, and activities (Cradle-to-site) in the conservation phase (Gómez de Cózar et al., 2019).

The calculation was performed using a functional unit of 1 m^2 and a building lifetime of 100 years. The calculations follow the LCA methodology outlined by LCA standards, NS 3720, Sustainability of construction works - Methodology for the assessment of performance of buildings (EN 15978), and/or ISO 14040/44 (Fufa et al., 2021). The LCA provides environmental impacts evaluation associated with all the stages of a product's life in all stages of the process from the extraction and processing of raw materials, to the manufacturing, packaging and marketing processes (Trovato et al., 2020).

Ideally, formulaic expression of mathematical framework is formulated to establish rationale of environmental impact profiling in defining the efficiency of lime-based mortar repair; based upon how green they are in terms of embodied carbon expenditure i.e., through mitigation and reduction of CO_2 emissions (Kayan, 2013).

CASE STUDIES

Melaka and George Town also have been listed as Malaysian UNESCO World Heritage Sites on 7 July 2008. The selection of the case studies in this research are made to achieve sustainability by using the life cycle assessment (LCA) of lime-based mortar repair in conservation of heritage buildings. Case studies are mainly selected in the core and buffer zone of Malaysian UNESCO World Heritage Site of Historic City of Melaka and George Town, Pulau Pinang.

Hong Kong and Shanghai Bank Corporation (HSBC)

The Hong Kong and Shanghai Bank Corporation (HSBC) building on Jalan Kota was constructed as a bank during the British era and it was built around 1912. The designed on the plan rectangular symmetry. The conservation of the HSBC was in 2009 it includes repairs, and replacement of damaged elements and structures with the same material which is lime-based mortar as the original. The major work repair of the outer wall by using lime-based mortar for the whole building. Figure 3 show the building structure of HSBC. During the conservation phase of HSBC, used of aggregates and sand were commonly rounded and contained small portions of a variety of materials such as stone dust, chalk, seashell, and ash. The proportion of binder to filler was 2:1 and 3:1.

Figure 3: Hong Kong and Shanghai Bank Corporation (HSBC)
Sources: Authors, 2023

Rumah Teh Bunga, George Town

'Rumah Teh Bunga' is also known as the Penang Malay Gallery, and it's classified under the residential category. It is located at No. 138, Hutton Road, George Town, Penang. It was built in 1893 by one of the richest Jawi Peranakan, Tuan Abdul Wahab, in the late nineteenth century (Volume, 2022). The major conservation that related to the use of lime-based mortar was in 2005 that involve the whole building wall. Figure 4 show the 'Rumah Teh Bunga' building structure.

Figure 4: 'Rumah Teh Bunga' Building
Sources: Authors, 2023

QUANTIFICATION OF CO2 EMISSION FOR LIME-BASED MORTAR REPAIR: EMBODIED CARBON COEFFICIENTS

According to Kayan et al. (2017), the cradle-to-site boundary of LCA, which includes the extraction, processing, and production of raw materials as well as the transportation of those resources to the building site, it is used to calculate the CO_2 emissions. There are various number of approaches to minimize the embodied CO_2 emissions through building repair, even if frequent maintenance interventions result in greater embodied carbon expenditure (Forster et al., 2013). It is well knowledge that the components of mortars, namely the binders and aggregates, the binder/aggregate and water/binder ratios and mostly influenced by porosity, which is in turn influenced by pore size, pore space distribution, and pore structure connectivity determines the mechanical and physical characteristics (Santos et al., 2018).For the case study buildings that used lime-based mortar repairs, the optimal values of the CO_2 emissions per kg km were obtained by using the pertinent LCA approach to ensure uniformity in the calculation processes. The functional unit of $kgCO_2e/kg/m^2$ will be use for the calculation of CO_2 emission and it was defined in kilograms of CO_2 emissions, equivalent per kilogram of lime-based mortar repair materials per m^2 of repaired masonry surface/area.

CO_2 Emission Factor from Lime-Based Mortar Repair Within Cradle-to-Gate

For the purpose of this research, carbon emission factors per kg km or $kgCO_2/kg/km$ were utilized based on per tonne-km for all 5 tonnes HGV/lorry based on UK average laden of vehicle loads (IFEU et al., 2014); (Defra, 2012); UK Government Greenhouse Gases (GHG) Conversion, 2016). Lime-based mortar repair materials supplied only by nominated suppliers were considered; entailing the shortest and most direct distance travelled for their transportation using similar transportation modes from the primary resourcing location to the building site (*di* in km). Thus, the carbon emission factor for transportation (Table 3) will be constant in all equations used in this research. To fulfil the goal of LCA approach, the functional units of $kgCO_2e/kg/m^2$ were defined in kilograms of CO_2 emissions, per kilogram of lime-based mortar repair materials, used on 1m2 of wall surface area. Using this functional unit, embodied carbon expenditure expended in lime-based mortar repair within cradle-to-gate boundary of LCA can be calculated based on the following Equation 1.

$$\Sigma \text{ ECEcradle} - \text{to} - \text{gate} = \boldsymbol{m_i} \times \boldsymbol{ecc_i} \times \mathbf{A_i}$$

Where,
$\boldsymbol{m_i}$ = mass (kg) of lime repair materials
$\boldsymbol{ecc_i}$ = embodied carbon coefficient ($kgCO_2e/kg$ per m^2) of lime-based mortar repair within cradle -to-gate of LCA
$\boldsymbol{A_i}$ = Area (m^2) of the repaired wall surface area

Table 1 shows the respective embodied carbon coefficients ($kgCO_2e/kg$) for lime plaster repair materials of the selected case study buildings.

Table 1: Embodied Carbon Coefficients ($kgCO_2e$/ kg) of Lime-Based Mortar Repair Materials

Embodied carbon coefficient, *ecci* (kgCO2e/kg)			
Materials / Case Study	**Lime**	**Sand**	**Brick Dust**
HSBC Building	0.69	0.00493	0.169
Rumah The Bunga	0.69	0.00493	0.169

Sources: Adopted from Jones, C., & Hammond, G. (2019). Inventory of Carbon and Energy (ICE) V3.0

The Embodied carbon Coefficients, *ecci* for the lime is 0.69 $kgCO_2e/kg$, for the sand and aggregate is 0.00493 $kgCO_2e/kg$ and for the brick dust is 0.169 $kgCO_2e/kg$ for both building. The values of embodied carbon coefficient, ecc_i in this research are evidently not precise (average figures) when applied to a general category of lime-based mortar repair materials. They were mainly derived from relevant manufacturers and applicable inventories such as Inventory of Carbon and Energy (ICE) Volume 3.0 by (Jones, C., & Hammond, G. 2019). Meanwhile, lime-based mortar repair materials for the respective buildings were determined based on specifications by conservation methods and techniques for wall structures and elements in Section 3.2 of "Guidelines on Heritage Building Conservation" (JWN, 2014).

Transportation Data

Table 2 shows material utilise in lime-based mortar repair of the selected case study with their respective primary resourcing locations and transportation distances, d_i (in km) to the building site. Transportation distance was calculated to the nearest kilometre, i.e., the shortest road distance travelled by land transportation, generated from Google Maps with the conversion of a mile to approximately 1.609 km. The mode of transportation for materials is usually a 5-tonne lorry (with a carbon emission factor of Ef, 0.43326 $kgCO_2e/kg/km$ for HSBC and 0.43326 for Rumah Teh Bunga).

Table 2: Distance of The Material to Buildings Case Study

Case Study	Materials	Resources Location	Site d_i (KM)	Total Distance (KM)	Remarks
HSBC Building	Sand	Bukit Senggeh, Selandar, Melaka	37.8	92.6	Sourced, produced and manufactured locally
	Lime	Kuari ISB Sdn. Bhd., Alor Gajah, Melaka	46.2		
	Brick Dust	Nurul Huda Sdn. Bhd., Alai Kandang, Melaka Tengah, Melaka	8.6		
Rumah Teh Bunga	Sand	Hong Heng Group, 25A&B, Jalan Pulai Hartamas 1 Medan Pulai Hartamas, 31300 Ipoh, Perak	111	268	Sourced, produced and manufactured locally
	Lime	Global Mix Sdn. Bhd, Lot PT 142868 Sungai Raja, 31300 Simpang Pulai, Perak Darul Ridzuan	157		
	Brick Dust	140, Jalan Hutton, 10050 George Town, Pulau Pinang	0		Sources made from the building brick

Sources: Authors, 2023

Resourcing location of lime mortar materials is determined based on where they are produced, processed, and manufactured, e.g., lime (quarry), sand (sand mining site), and brick dust (processing plant/building site), respectively. Results in Table 2 indicate that the greater the transportation distance (268km), the greater the CO_2 emission during materials delivery. In the case of the HSBC building and Rumah Teh Bunga, the raw material (lime, sand, and brick dust) used for building conservation is taken from the nearest resourcing location (salvage) to lowest the CO_2 emission.

It must be noted that the transportation distance from the secondary resourcing locations, such as from various warehouses, ports, airports, or other points of procurement, either from numerous suppliers or manufacturers was not considered. The increases of CO_2 emission are due primarily to fossil fuel (Fong et al., 2008). The impact of the transportation of raw materials to the site is non-negligible and, according to (Guerlain et al., 2019) it accounts for at least 30% total represented CO_2 emissions were associated with transportation of local materials respectively.

CO_2 Emission Lime-Based Mortar Repair Within Gate-to-Site

Total embodied carbon (kgCO$_2$e/kg) for lime-based mortar repair with inclusion of transportation data (emission factor and distance), total embodied carbon expenditure (kgCO$_2$e/kg) expended on lime plaster repair within gate-to-site could be calculated using the following Equation 2: Embodied Carbon Expenditure within Gate-to-Site. Table 3 shows the Embodied Carbon Expenditure for lime-based mortar repair materials transportation.

$$\mathbf{\Sigma}\ \text{ECEgate} - \text{to} - \text{site} = m_i \times ef_i \times d_i$$

Where;
$\boldsymbol{m_i}$ = mass (kg) of the lime repair materials transported in every km distance
$\boldsymbol{ef_i}$ = carbon emission factor per kg km for lime plaster materials transportation within cradle-to-gate; in this case is a lorry up to 5 tonnes ($kgCO_2e/kg/km$)
$\boldsymbol{d_i}$ = shortest distance (km) for delivery of lime plaster

Table 3: Embodied Carbon Expenditure, *efi* ($kgCO_2e/kg/km$) for lime-based mortar repair materials transportation

Case Study	Material	ef_i ($kgCO_2e/kg/km$)	Remark
HSBC Building	Sand	0.43326	Based on 5 tonne HGV/lorry, (%) weight laden - average laden and values
	Lime		
	Brick Dust		
Rumah Teh Bunga	Sand	0.43326	Based on 5 tonne HGV/lorry, (%) weight laden - average laden and values
	Lime		
	Brick Dust		

Sources: Authors, 2023

Total CO_2 Emission Lime-Based Mortar Repair Within Cradle-to-Site
The overall total of embodied carbon expenditure for the repaired wall surface area of the selected case studies within cradle-to-site could be calculated using the following Equation 3: Overall Total of Carbon Expenditure from Cradle-to-Site.

$$\mathbf{\Sigma}\ \text{ECEcradle} - \text{to} - \text{site} = \mathbf{\Sigma}\ \text{ECEcradle} - \text{to} - \text{gate} + \mathbf{\Sigma}\ \text{ECEgate} - \text{to} - \text{site}$$

Where;
Σ ECEcradle−to −site = Overall total of Embodied Carbon Expenditure ($kgCO_2e$) in lime repair within cradle-to-site boundary of LCA

To test the efficiency of lime-based mortar repair options base on selected maintenance period will be analyse further in the Total Environmental Maintenance Impact (EMI) (table 7).

RESULT

The results of this study were developed using generated LCA data of embodied carbon expenditure ($kgCO_2e/kg$), principally, to improve the efficiency of lime-based mortar repair of the selected case studies in terms of embodied carbon expenditure.

Total Mass, m_i (kg) and Mass kg/m^2 of Lime-Based Mortar Repair Materials

Table 4 shows that m_i kg of lime repair materials for each case study relies upon different number of lime repair applied on total repaired wall surface area (A_i) (m^2). This indicates that A_i (m^2) and number of lime repair (tn) were highly influenced by total mass, m_i (kg) of materials used in lime-based mortar repair for all selected buildings. Theoretically, increment in total CO_2 emissions from lime-based mortar repair within cradle-to-site boundary of LCA is highly influenced by increasing numbers of applied lime repair (tn) on exterior wall surface of the selected buildings (as shown by results in Table 4).

Table 4: Total Mass, m_i (kg) and Mass kg/m^2 of Lime-Based Mortar Repair Materials for Case Studies

Mass, m_i (kg)					Mass kg/m^2				
Case Study	**1 Coat**	**2 Coats**	**3 Coats**	**Total**	**Wall surface area, A_i (m^2)**	**1 Coat**	**2 Coats**	**3 Coats**	**Total**
HSBC Building	2578.64	6702.94	1030.44	10312.02	126.28	20.42	53.08	8.16	81.66
Rumah Teh Bunga	2625.86	7877.56	1125.86	11629.28	160.80	25.92	58.58	13.66	98.16

Sources: adopted by (Kayan et al., 2021)

Functional units of embodied carbon per m2 of repaired wall surface (kgCO2e/kg/m2)

Table 5 establishes functional units of kgCO_2e/kg/m^2 or normalised overall total of embodied carbon expenditure in lime-based mortar repair, undertaken on 1m^2 of wall surface repaired area of the respective selected buildings. The results of this table indicate that overall total functional unit of embodied carbon is influenced by lime-based mortar materials profile and transportation data.

Table 5: Functional Units of Embodied Carbon Per m2 (KgCO2e/Kg/m2) of Repaired Wall Surface of Case Study Buildings

Life Cycle Assessment (LCA) Boundary									
Case Study	**Lime-Based Mortar Materials**	**Lime Plaster Materials Ratio**	**Mass (kg)/m^2**	**Distance to Building Site, d_i (km)**	**Embodied Carbon Coefficient (kgCO2e/kg)**	**Carbon Emission Factors, ef_i (kgCO_2e/kg/km)**	**Cradle-to-Gate Total (kgCO_2e/kg m^2) (A)**	**Gate-to-Site Total kgCO2e/kg/m2 (B)**	**Cradle-to-Site Overall Total kgCO_2e/kg/m^2 (A+B)**
HSBC Building	Sand	1	16.33	46.20	0.690	0.43326	11.268	326.870	338.138
	Lime	3	48.99	37.80	0.005		0.2410	802.320	802.561
	Brick Dust	1	16.33	8.60	0.169		2.760	60.850	63.610

Rumah Teh Bunga	Sand	1	16.33	157.00	0.690	0.43326	11.268	1136.200	1147.468
	Lime	3	48.99	111.00	0.005		0.2410	2409.910	2410.150
	Brick Dust	1	16.33	0.00	0.169		2.760	0.000	2.760

Sources: Authors, 2023

Longevity

The longevity of lime plaster repair. In order to test efficacy of adopted LCA, the longevity of lime plaster repair (function of number of frequencies of repair) was evaluated within an arbitrary period (in this case 100 years). This can be expressed in the following Equation 4: Longevity of lime -based mortar repair.

$$fx = \frac{x_{years}}{i}$$

Where;
f_x =longevity of lime plaster repair options for respective numbers of lime coatings applied within an arbitrary period
x_{years} = arbitrary period (years) of maintenance intervention lime repair options
i = interval years of lime plaster repair

Using Equation (4), the longevity of lime repairs within an arbitrary 100-year period was generated (refer table 6).

Table 6: Overall total of EMI ($kgCO_2e$) for Lime Plaster Repair Within Cradle-to-Site of Selected Arbitrary 100-Year Period

Case Study	Lime-Based Mortar Materials	Total EMI (kgCO2e) within cradle-to-site of lime plaster materials ΣECEcradle−to−site	Frequency of lime plaster repair in every arbitrary 100-year period f_x	Overall total EMI (kgCO2e) within cradle-to-site of selected arbitrary 100-year period ΣEMI 100years= ΣECEcradle−to− site X f_x
HSBC Building	Sand	101347.403	4	405389.612
	Lime	42700.067		170800.268
	Brick Dust	8032.6708		321130.6832
Rumah Teh Bunga	Sand	387552.281	4	1550209.12
	Lime	184512.854		738051.416
	Brick Dust	443.808000		1775.2320

Sources: Author, 2023

Total Environmental Maintenance Impact (EMI)
Total EMI (kgCO_2e) in this study was calculated using respective longevity of repair within the arbitrary period. This can be expressed in the following Equation 5: Total Environmental Maintenance Impact (EMI)

$$\mathbf{\Sigma}\ \text{EMI} = \mathbf{\Sigma}\ \text{ECEcradle - to - site x } f_x$$

Where;
f_x = longevity of lime plaster repair for respective numbers of lime coatings applied within the arbitrary period
Σ EMI = Total EMI (kgCO_2e/kg)

Table 7 shows the total EMI within cradle-to-site of LCA for every lime coating applied on the wall surface of the selected buildings. In the context of whole life cycle, the number and thickness of applied lime coating as well as mixture ratio of lime plaster materials used will determine the durability of wall surface area. Theoretically, the higher the longevity of repair the fewer the number of repairs needed.

Table 7: Total EMI (kgCO_2e) of Lime-Based Mortar Repair Within Cradle-to-Site

Functional Units (kgCO2e/kg m2) and LCA Boundary									
Case Study	**Lime-Based Mortar Materials**	**Wall surface area, A_i (m^2)**	**Cradle-to-Gate (A)**	**Gate-to-Site (B)**	**Cradle-to-Site A+B=(C)**	**Total EMI (kgCO_2e) and LCA boundary**			**Total EMI (kgCO_2e) for all Materials**
						Cradle-to-Gate A_i X A	**Gate-to-Site A_i X B**	**Cradle-to-Site A_i X C**	
HSBC Building	Sand	126.28	11.27	326.87	338.14	1423.18	41277.14	42699.06	304159.40
	Lime		0.24	802.32	802.56	30.43	101316.97	101347.28	
	Brick Dust		2.76	60.85	63.61	348.53	7684.14	8032.67	
Rumah Teh Bunga Building	Sand	160.80	11.27	1136.20	1147.47	1810.61	182700.96	184513.18	1145016.77
	Lime		0.24	2409.91	2410.15	38.75	387513.53	387552.12	
	Brick Dust		2.76	0.00	2.76	443.81	0.00	443.81	

Sources: Author, 2023

It must be emphasised that the total EMI in this study could only be accurate if all the lime-based mortar repairs were undertaken immediately after their life expectancy has concluded. This also must depend on the adopted LCA calculation procedure's ability to draw rationale upon number of lime coatings applied and their respective longevity of repair.

DISCUSSION

Results from Table 7 show that EMI of lime-based mortar repair of the selected heritage buildings is determined mainly by wall surface area, A_i (m^2) and number of lime coatings (*tn*). Meanwhile, LCA testing results are significant as they indicate different parameters of lime coating materials of lime-based mortar repair, i.e., mass, m_i (kg), mass kg/m^2, functional units kgCO_2e/kg/m^2, embodied carbon coefficient, ecc_i (kgCO_2e/kg) and transportation data (distance to building site, di km and carbon emission factors of mode of transportation, ef_i (kgCO_2e/kg/km) and longevity of repair within arbitrary periods, f_x.

All these parameters as certain the efficacy of lime-based mortar repairs options in terms of embodied carbon expenditure (CO_2 emissions). Practically, the most effective lime-based mortar repairs in terms of low carbon repair and sustainable maintenance management of heritage buildings are the one that most suitably accommodates adopted LCA approach and all parameters. It must be emphasised that many examples of applied lime coatings are still functioning satisfactorily in heritage buildings that are several hundred years old. Meaningfully, generated total EMI based on Equation (3) shows the significance influences of long-term cumulative impact in terms of embodied carbon expenditure for sustainability of lime-based mortar repairs option in heritage buildings.

Research results demonstrated that calculation procedures underpinned by LCA approach have the ability to determine the cumulative EMI. Adopted LCA approach had established its beneficial value, i.e., practically effective in evaluating efficacy of lime-based mortar repairs in terms of embodied carbon expenditure within selected boundaries of LCA and arbitrary maintenance periods. When placed in the context of a 100-year maintenance period, testing of LCA approach results in Table 7 show that Sanitary Board Building has the highest overall total EMI of 2290035.77 kgCO_2e, with the utmost frequency of lime-based mortar repair, f_x of 4.

Conversely, HSBC Building produced the lowest overall total EMI of 897320.295 kgCO_2e with moderate frequency of lime-based mortar repair, f_x of 4. The general, lime commonly procured and resourced locally incurs small-scale production and contributes to less carbon emissions. It is revealed that transportation of imported of lime and sand for Rumah Teh Bunga building had contributed to significantly high embodied carbon expenditure. Thus, this research makes a strong case for procuring locally sourced materials in repair of heritage buildings, which should be encouraged as it will reduce CO_2 emissions.

CONCLUSION

The results of this study show that generated total embodied carbon expenditure expended from lime-based mortar repair of selected heritage buildings can be evaluated and tested based on LCA approach. It is discovered that the highest longevity of lime-based mortar repair technique had resulted in the lowest embodied carbon expenditure within the cradle-to-site boundary of LCA and arbitrary maintenance period.

Meanwhile, generated EMI has shown its ability to reduce embodied carbon expenditure, thus providing guidance for the flexible selection of sustainable repair options. This provides a useful tool for making decisions on materials and suppliers for the conservation of heritage buildings.

Beneficially, this research will help heritage building maintenance managers or lime-based mortar repair materials manufacturers to utilise embodied carbon expenditure data and give preference to locally sourced, produced, and manufactured materials over imported materials to reduce the cumulative amount of carbon emissions.

As our society moves towards an environmentally focused economy and sustainable maintenance management solutions and to achieve SDGs, this will be welcomed. As sustainable repair options in the building industry become more prevalent, the adopted LCA approach of this study can be converted into a supplementary financial cost in the maintenance decision-making process.

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