Global warming potential comparison of lime and cement-based masonry repair mortars

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ABSTRACT:

Lime has been used in masonry mortars for millennia, and many old buildings remain standing today with purely lime technology, despite its low compressive strength compared with cement. Modern approaches tend towards stronger and more durable materials to minimise repair cycles and labour costs, but at the detriment of traditional buildings. Cement-based mortars used to repair historical masonry has accelerated the decay of old buildings, which had previously been in reasonable condition for decades. This has seen the conservation industry return to consider lime technologies as a more compatible solution for solid masonry buildings.

Life cycle analysis is used to assess environmental impacts of materials across various categories throughout the different stages of their interaction with humans and the wider environment. Despite an increasing number of life cycle analyses investigating mortars, few studies compare the impacts of cement-based and lime-based mortars, and those that do rarely consider the implications for heritage repair and maintenance.

Life cycle analysis is used to estimate global warming potential associated with a repair intervention taking historical sandstone ashlar masonry as a case study, and considering iterative replacement cycles under two different repair methods. Global warming potential per unit area (m^2) over 100 years for cement-based mortar is found to be between 43 – 348 % greater than scenarios using lime-based mortars. Sensitivity analysis finds the choice of functional unit to greatly impact outputs, such that when comparing mortars, that with highest emission intensity can change. Careful selection is needed of the most relevant functional unit for a specific case.

1 INTRODUCTION

Climate change is already having a devastating impact on livelihoods and the World Bank (2021) predicts that 216 million people could be displaced due to climate change by 2050. It is therefore paramount that all sectors keep a global focus to mitigate greenhouse gas (GHG) emissions to ensure global temperature rise remains below the Paris Agreement target of 1.5°C.

According to the International Energy Agency (2019), in 2018 buildings and construction released 39% of global greenhouse gas emissions, taking the largest share of all sectors, and the total global emissions from buildings continue to rise. Furthermore, the cement industry is responsible for around 8% of global GHG emissions (Andrew, 2019).

Life cycle assessment (LCA) is a tool for evaluating the environmental impacts of materials and products over their lifetime through various impact categories. The category most relevant to climate change is global warming potential (GWP), which quantifies the level of greenhouse gas emissions caused by the subject throughout its life cycle. A cradle-to-grave LCA considers all stages of a products lifetime from raw material extraction, through processing, transport, usage and demolition, while cradle-to-gate only considers impacts up to the point that the product is ready to leave the manufacturer's gate. Considering the full life cycle is important for building materials as the usage and demolition stages can vary depending on the product and its application (Churcher, 2013).

According to the English Housing Survey (Ministry of Housing, 2020) over 73 % of dwellings in England were more than 39 years old and 20.1 % were built before 1919, while 29.2 % of dwellings had solid walls.

Traditional buildings of solid wall construction allow moisture transport through liquid capillary flow and through vapour diffusion, however they avoid damp and mould through heating, ventilation and through the use of materials that allow rapid drying such as traditional lime mortar (Hughes, 2020, Little et al., 2015).

More recently it has been found that modern cement mortars are accelerating substrate decay when used on solid masonry and are often considered incompatible with traditional masonry buildings (British Standards Institution, 2013, Nežerka et al., 2015). Compatible repair materials should prolong the lifetime of the substrate and therefore be sacrificial in nature (Hughes and Valek, 2003). An increased decay rate due to incompatible materials is evident on many masonry structures (Mitchell, 2007, van Hees et al., 2004). This consequently increases the amount of material needed for subsequent repairs, compounding environmental impacts, however, this impact has not yet been quantified.

1.1 *Goal and scope*

This study aims to compare the impact of commonly used cement mortar to a best practice repair mortar for the conservation of historical sandstone structures. This study considers only the impact category global warming potential (GWP100) which is a characterization model for radiative forcing over 100 years, measured in mass of carbon dioxide equivalent emissions (kgCO_2eq), as defined by ISO/TR 14047 (BSI, 2012).

The lifecycle stages considered are: extraction of raw materials, processing, manufacturing and use stages, including carbon sequestration and maintenance cycles, however transport and demolition stages are ignored as these are assumed equal in all cases. Emissions associated with binders are combined with those for other mortar components at relevant mix ratios. Two different masonry repair approaches are applied along with deterioration rates to find the impact of a traditional lime conservation approach compared to a cement mortar considered incompatible.

1.2 *Literature review*

Santos et al. (2021) reviewed LCAs on mortars and although they found 124 studies, the majority focused on cement-based mortars, while many did not provide detailed boundary conditions. Comparison between studies with undeclared or different boundary conditions is difficult, highlighting the importance of LCAs that compare multiple mortar mixes to the same boundary conditions. Several LCA studies have compared modern cement-based and traditional lime-based mortars, a summary of these is found in Table 1.

In their cradle to gate LCA study Diaz-Basteris et al. (2022) compared mortars of cement and lime over 100 years, and found that the binder production had the highest impact on GWP.

Pineda et al. (2017) studied both physical and environmental performance of grouts using different binders: cement, hydrated air lime and natural hydraulic limes (NHL). Usage and demolition were excluded from the LCA, however, as the intended use was in historical structures an incompatibility factor was developed based on chemical and mechanical characteristics. Silva et al. (2015) also studied compatibility of mortars comparing similar binders and included physical properties such as pore size distribution, water absorption and drying index. However, neither of these studies related compatibility to environmental impacts.

Table 1. Summary of lifecycle assessments comparing global warming potential (GWP) of cement-based and lime-based mortars. Values in parenthesis denote GWP after sequestration due to lime carbonation.

Reference	Life cycle type	Life cycle inventory data source	Materials (fuel source in parenthesis)	Binder GWP	Mix ratio (mass based)	Mortar GWP
				$kgCO_2eq$/ton		$kgCO_2eq$/ton
(Pineda et al., 2017)	Cradle – gate	Ecoinvent	Hydrated air lime	766.4		
			Cement	833.4		
			Hydrated air lime, pozzolan, limestone		1:1:0.48	350
			Cement, silica fume		1:0.33	500
(Diaz-Basteris et al., 2022)	Cradle – grave	Collected by survey, interview & production site visits	Hydrated lime (coke)	1518 (983)		
			Hydrated lime (gas)	1193 (658)		
			Cement (coke)	1538		
			Cement (gas)	1193		
			Hydrated lime, sand (coke)		1:2.33	587
			Cement, sand (coke)		1:2.33	737
(Moropoulou et al., 2005)	Cradle – grave	n.a.	Hydrated air lime, sand		1:2.33	0.17
			Hydrated air lime, sand + 5% metakaolin (pozzolan)		1:2.8:0.2	0.16
			Cement, sand		1:2.33	0.23

2 METHODOLOGY

When using LCA studies to inform material choices each study must be reviewed carefully to ensure that the comparison is relevant to the specific application. Mortar mixes are herein designed to represent the most common cement-based approach compared to a repair mix recommended by conservation literature. The cement mortar is a 1:5 volume ratio sand and cement, using local soft building sand and widely available Multicem CEMII. The lime mortar is intended to replicate a traditional mix using CL90 quicklime pieces (5-0mm), well graded washed sharp sand sieved to a maximum of 2mm, and wood ash from a commercial biomass boiler sieved to 2mm as a pozzolanic additive (Copsey, 2020, English Heritage, 2011). The mortar mix proportions are detailed in

Table 2 (not the exothermic reaction of water and lime produced steam).

Table 2. Mortar mix proportions

Mortar mix	Components	Volume ratio	Mass ratio	Binder mass per mortar volume	Water/binder ratio	Flow rate
				kg/m3	kg/kg	mm
Cement	Cement, building sand	1:5	1:5.8	234	1.5	143.5
Lime-ash	Quicklime, sharp sand, wood ash	1:3:0.19	1:2.9:0.1	338	2.1	132.7

Sands were dried to constant mass at 70°C ensuring water content was controlled. Dry ingredients (sands and binder) were first mixed before water was added meaning a strong exothermic reaction took place for the lime mortar and steam was released. Mortars were mixed by hand for 5 minutes following BS EN 1015-2 (BSI, 2007a), flow rate was determined by procedures in BS EN 1015-3 (BSI, 2007b).

3 INVENTORY ANALYSIS

Life cycle inventory (LCI) figures tend to account for cradle to gate emissions including material extraction, transport to plant and manufacturing. Figures for GWP of lime and cement binders vary considerably according to (Anderson and Moncaster, 2022) and as seen in Table 1, highlighting the importance to use data for the actual materials used. Inventory cradle-gate figures are taken for the specific products used. GWP for quicklime is taken from the manufacturer's report (Lhoist, 2022), and although there is no explanation of calculation methods this figure is very similar to the value commissioned by the European Lime Agency (EuLA) presented in the GABI database (EESAC, 2019), which is fully compliant with the ILCD Data Network and standards ISO 14040 and 14044. The GWP for cement (BRE Global Ltd., 2019) is taken from an environmental product declaration (EPD) verified by BRE Global to be compliant with BS EN 15804 (based on EN ISO 14044) and is a similar value to many other EPD's for similar products. For sand the GWP is taken from a cradle to gate LCA conducted by Grbeš (2015) of silica sand following the ReCiPe method, assuming here all sand followed the basic wet processing. The GWP of water is taken from Ecoinvent database. The wood ash pozzolan is a waste product so is considered to have zero GWP.

Several functional units are used in this study: initially the GWP per mass of mortar is calculated ($kgCO_2eq/kg$) without considering maintenance or replacement cycles, then GWP is calculated per unit area of masonry ($kgCO_2eq/m2$) for a particular case considering replacement cycles as explained in section 5.

4 IMPACT ASSESSMENT

The GWP for each mortar is presented in Table 3. As a higher proportion of binder was used in the lime-ash mortar this made up a higher proportion of the impact.

Table 3 Global warming potential and carbonation percentages for mortars used.

Mortar	GWP per mass binder	% Process emissions	% Carbonation	Mass binder per volume mortar	GWP per mass mortar	GWP per volume mortar
	$kgCO_2eq/kg$	%	%	kg/m^3	$kgCO_2eq/kg$	$kgCO_2eq/m^3$
Lime-ash	1.204	65.7%	84.7	338	0.112	184
Cement	0.826	n.a.	n.a.	234	0.105	198

Carbonation of the lime-ash mortar is slightly reduced due to the calcium hydroxide consumed by the mass of ash pozzolan (1.294 g $Ca(OH)_2$ consumed by 1 g ash, value taken from Pavlíková et al. (2019) who used the Chapelle test on wood-based biomass ash). As quicklime (CaO) was used which expanded with the addition of water, the percentage of the available free lime consumed by the ash was calculated based on experimental results. It is assumed that 90% of the remaining available lime carbonates before end of life (as reported by EuLA (Ecofys, 2014) and in agreement with Figueiredo (2018)), giving 85% carbonation of the $Ca(OH)_2$ available in 1 kg CaO.

5 COMPATIBILITY IMPACT

The historical precedent viewed in heritage structures around the world suggests that traditional lime pointing can remain in good condition for many decades, however, this depends on application efficacy, curing conditions, exposure and weather conditions (Papayianni and Hughes, 2018). Pointing mortars applied correctly are expected to last at least 30 years, and normally 50-100 years according to Maurenbrecher et al. (2001), whereas Boynton and Gutschick (1964) suggest 15 years for cement tuck pointing and 50-500 years for lime mortars. A conservative estimate therefore is to assume repointing is necessary every 35 years, meaning raking out of old mortar and repointing would be carried out three times over 100 years.

Despite the widely stated incompatibility of cement mortars on historical masonry structures, only one study has been found to focus on quantifying the effect of cement repointing on the deterioration rates of such structures. To estimate deterioration rates of medieval sandstone churches André et al. (2014) took masonry sections that retained their original finish as (non-decayed) reference points and compared these to more degraded areas using three dimensional LiDAR laser scanning. For white sandstone they found that areas retaining traditional lime mortars decayed at a rate of 3.5-4.8 mm/century while areas repointed with cement mortar in the 20th century degraded between six to seven times faster (21.2, and 35.5 mm/century), and in some areas up to ten times (André et al., 2014).

Masonry repair work can follow different strategies, and here two opposing strategies are proposed, named as method A and method B. Method A would follow the removal of deteriorated stone and mortar, repointing joints flush with the substrate and use of minimal "plastic" (mortar) repair to ensure rain water drains off. Method B involves restoring the stone-work back to the original face using "plastic" mortar repair, thus large areas of decayed stone are rendered and joints highlighted by inscribing a line into the mortar. An example of a historical sandstone masonry wall can be seen in Figure 1 with representations of methods A and B depicted. These were used to estimate percentage area and volume of mortar needed per functional unit ($1m^2$) of stone masonry under each repointing method.

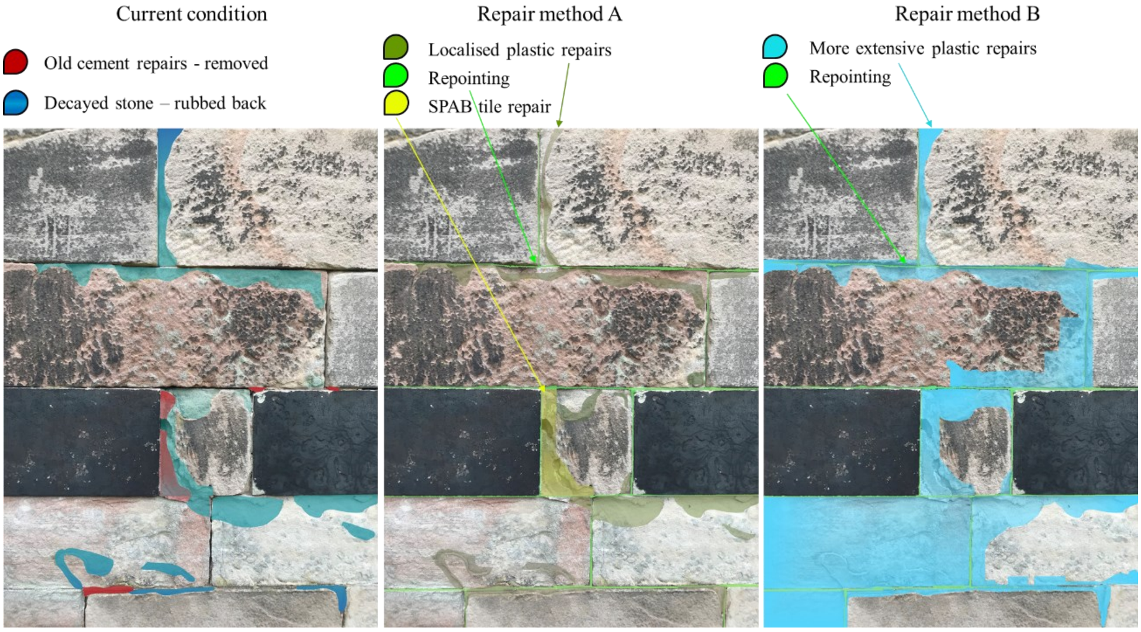

Figure 1. Masonry decay and repair methods on representative masonry at the grade II* listed Elizabethan Lymm Hall (Author, 2021)

In the example case study (Fig. 1): method A requires repointing joints and plastic repair accounting for 8% of the area, whereas method B requires that all degraded areas are covered with mortar, at 26% of the area. Joints are on average 3mm wide and assumed repointed to 20mm deep, plastic repairs are assumed on average 5mm deep and one deeper area (highlighted in yellow in Figure 1) is assumed 30mm deep. For repair method A this deeper area is filled with stone tiles taking up half the volume (leaving the other half filled with mortar), whereas for method B the whole volume is filled with mortar.

For each repair method the total volume of mortar needed is calculated for the current condition. Decay rates from (André et al., 2014) were used taking the average traditional mortar decay rate 4.15 mm/century for lime-ash mortar, and the average decay rate after cement repointing 28.35 mm/century for cement mortar. For each this was applied for a 35-year intervention and then a 70-year intervention and aggregated along with the initial repair to determine the material required for three interventions over one century. This enabled calculation of GWP for each method.

6 RESULTS & DISCUSSION

It is plausible that a laborer unaware of compatibility issues would choose method B as a lack of research would imply little desire to retain the aged historical patina, whereas method A would be a more conservative approach, following guidance form those such as the Society for the

Protection of Ancient Buildings (Slocombe, English Heritage, 2011). Therefore, Table 4 presents impacts for GWP100 for the lime-ash mortar under method A, along with that for cement mortar under method B. A sensitivity analysis evaluated the impact of cement mortar under repair method A. A further sensitivity check used the LCI data of Diaz-Basteris et al. (2022) for lime and cement binders, with results reported in Table 4.

Table 4 Volume of mortar used and GWP100 for mortars under different repair methods

Mortar	Repair method	Volume of mortar used in 100 years per m^2 masonry	Total GWP100 for $1m^2$ stone masonry	% increase over lowest GWP	Total GWP100 for $1m^2$ stone masonry using LCI data from [1]	% increase over lowest GWP
		m^3/m^2	$kgCO_2eq/m^2$	%	$kgCO_2eq/m^2$	%
Lime-ash	A	0.0034	4.3	lowest	4.2	lowest
Cement	B	0.0188	13.2	209	18.9	348
Cement	A	0.0103	6.1	43	8.7	106

[1] (Diaz-Basteris et al., 2022)

The results emphasize the importance of both the selection of LCI data and the choice of repair method, altering the GWP by 1.43 and 2.18 times respectively in the most significant cases. Comparing results to those of Diaz-Basteris et al. (2022) who found that a cement-based mortar produced 26% more emissions than a lime-based mortar per ton over 100 years, here the GWP of the cement mix was 43 – 348 % higher than the lime mix per m^2 of masonry. There are several differences between the studies, most notably the present study considered maintenance cycles and the impact of cement on masonry decay. If mortars are compared using repair method A for both, the GWP of the cement mortar was 1.43-2.06 times that of the lime-ash mortar, depending on the LCI source data chosen. In all cases the cement mortar has a higher GWP than the lime-ash mortar, however, the choice of repair method can have a greater influence on GWP than the binder type.

The approach illustrated in the present study has developed that of Pineda et al. (2017) by incorporating the impact of incompatibility on GWP.

The present work has considered one case study for repair and although it was intended to be representative, the calculation of impacts depend on the initial condition. Furthermore, the decay factors are extracted from the study of a different building and ideally would be determined on a case-by-case basis.

7 CONCLUSIONS

This study set out to compare GWP100 of a commonly used cement mortar to a best practice lime mortar for the repair of one meter squared of historical sandstone masonry. The approach incorporated the increased deterioration caused by incompatible cement mortars compared to a standard deterioration rate applied to the traditional lime mortar. The results imply that cement mortars have a higher GWP100 by a factor of 1.43 to 4.48, depending on the LCI source data and repair method used. In the case study presented the use of lime instead of cement mortar saves up to 8.93 $kgCO_2eq$ per meter squared of stone masonry over 100 years (using product LCI data).

Sensitivity analysis investigated the impact of the repair strategy used as well as the source LCI data, finding that both have a significant effect on the results, thus emphasizing the need for a case-by-case approach if accurate GWP is sought when comparing mortars.

In all scenarios the cement mortar remained the most emission intensive, highlighting the importance of selecting appropriate and compatible materials not only for the longevity of historical masonry, but also to minimize GHG emissions associated with the volume of material required for repairs.

8 ACKNOWLEDGEMENTS

The Low Carbon Eco-Innovatory Research Programme funded through the European Regional Development Fund at the University of Liverpool as well as Ecospheric Ltd. are acknowledged for financial support. Any opinions, findings and conclusions expressed in the manuscript are those of the authors and do not necessarily reflect the views of the funders.

This is a preprint of the following chapter: Dickens, L.A. & Di Sarno, L., Global Warming Potential Comparison of Lime and Cement-Based Masonry Repair Mortars, published in Towards a Carbon Neutral Future, edited by Papadikis, K., Zhang, C., Tang, S., Liu, E., Di Sarno, L., 2024, Springer, reproduced with permission of Springer Nature Singapore Pte Ltd.. The final authenticated version is available online at: https://doi.org/10.1007/978-981-99-7965-3_59.

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