Life cycle assessment of rammed earth made using alkaline activated industrial by-products

IOP Conf. Series: Earth and Environmental Science **323** (2019) 012143 doi:10.1088/1755-1315/323/1/012143

Life cycle assessment of rammed earth made using alkaline activated industrial by-products

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Abstract. Given increasing environmental concerns, lower energy building materials are being developed to reduce greenhouse gas emissions. The ancient technique rammed earth has been combined with modern industrial waste products to both reduce greenhouse gas emissions and reduce waste. The new rammed earth mixes have been developed using alkaline activation (sodium hydroxide) of industrial by-products: fly ash, ground granulated blast furnace slag and silica fume. This paper explores the 'cradle-to-gate' life cycle assessment, assessing global warming potential of these rammed earth materials, considering acquisition of raw or recycled materials and processing to final product of residential building envelope. These are compared with commonly used building envelope materials, brick veneer and cavity brickwork, and the more common rammed earth variety, cement-stabilised rammed earth. Results show that greenhouse gas emission savings can be made using these rammed earth mixes compared to the control building materials while achieving comparable or better material properties. Greenhouse gas emissions associated with the building envelope materials are reduced by more than half or one third when compared to cavity brickwork or brick veneer respectively. Following testing of the waste products in surplus in a given area, the same process could be followed for any geographic location.

1. Introduction

Globally, buildings account for a significant portion of total energy use throughout the full life cycle, from raw material acquisition and processing, through the operation stage and finally, at end of life. Although in Australia per capita building sector energy use has been declining, population increases will result in absolute growth over time [1]. As such, buildings are an important area where greenhouse gas emissions (GHGE) reductions could be made. Average house sizes have been increasing and, as improvement are made in the operational energy stage, energy spent on the structure (known as embodied energy) becomes a higher portion of total emissions [2].

Further to GHGE, the building industry uses around 30-50% of raw materials and is responsible for approximately 40% of landfill waste in OECD member countries [3,4]. These statistics highlight the importance of repurposing waste both to reduce virgin material use and to reduce landfill waste.

Rammed earth (RE) is an environmentally friendly building material when made using traditional methods; natural inclusions such as clay and straw were used as binders [5,6]. However, the more modern versions of RE are 'stabilised,' incorporating more energy intensive materials; in the last century it has become more common to add stabilisers such as lime, bitumen and cement, with 5-10 wt.% cement becoming the most common [7,8]. While improving material properties, cement addition significantly reduces environmental benefits. The cement industry is responsible for 6% of annual GHGE with around one tonne of CO_2 emitted per tonne of clinker produced, an intermediate product in cement production [9,10]. New RE mixes have been developed by the authors replacing cement with industrial by-products to lower GHGE associated with embodied energy of buildings and reuse waste.

Life cycle assessment (LCA) is being increasingly used to determine environmental impacts of any product or process. In the context of embodied energy in the building industry, LCA aids better material selection or can be used to identify problem areas and improve processes to reduce GHGE. In this study, LCA is used to determine GHGE associated with embodied energy of the newly developed RE mixes as well as the more common version cement-stabilised RE. The aim of the study is to determine potential benefits from a global warming perspective of using the RE mixes made with industrial by-products compared to more common building envelope materials.

2. Materials and methodology

2.1. Rammed earth materials

RE mixes being assessed are listed in Table 1. The mix most commonly used in Western Australia (WA), crushed limestone (CL) stabilised with cement, is used as a control mix. The second mix, CL_AA, replaces the cement with alkaline activated aluminosilicate materials, mostly industrial by-products. The third mix replaces the CL with recycled brick and concrete (RBC). The industrial by-products used are fly ash, ground granulated blast furnace slag (GGBFS) and silica fume. A by-product of coal combustion, it is estimated there are 225 million tonnes of fly ash currently stockpiled in Australia [11]. GGBFS is a by-product of iron and steel production. It is popular as a supplementary cementitious material (SCM) used by the concrete industry. The GGBFS produced in Australia is fully or largely used by the concrete industry with more imported [12]. Silica fume is produced as a by-product during silicon metal and alloys production and is supplied to the market by primary manufacturers based in Bunbury, WA. It is also used as a SCM by the concrete industry. Kaolin clay is available commercially. NaOH was prepared as a 12M solution. Additional water was then added to each mix to reach the optimum moisture content, determined according to AS 1289.5.2.1—2003 [13].

Table 1. RE mix designs.

Mix	UCS (MPa)	Mix components (%)								
		CL	RBC	Kaolin	Fly ash	GGBFS	Silica fume	Cement	NaOH pellets	Water
CL_C	11.1	81.5	-	-	-	-	-	8.2	-	10.3
CL_AA	19.8	73.0	-	3.7	7.3	3.7	2.9	-	1.65	7.8
RBC_AA	24.1	-	73.0	3.7	7.3	3.7	2.9	-	1.65	7.8

2.2. Sustainability analysis goal and scope

This LCA is completed in accordance with ISO 14044:2006(E) [14] and EN 15804:2012+A1:2013 [15] specifically for coproduction methodology. Results could be used by government in development of sustainable building policies, designers and builders, and to assist the general public when making material choices while building their own homes. The LCA has been completed as a ‘cradle-to-gate’ approach, incorporating material acquisition through to production of the final product, an external wall of a residential structure. Two common residential building envelopes were selected as controls to

IOP Conf. Series: Earth and Environmental Science **323** (2019) 012143 doi:10.1088/1755-1315/323/1/012143

compare with the RE wall designs: brick veneer (BV) and cavity brick (CB). Brick veneer is the most common residential construction type around Australia while cavity brick is still commonly used in WA.

The functional unit (FU) considered is one vertical square meter of an external load-bearing wall. Envelope walls have been designed to meet requirements of Australia's climate zones 4-6, in which around 70% of the population resides [16]. To meet Australia's National Construction Code 2016 (NCC) 'Deemed-to-Satisfy' Provisions, two options are available: a house may meet the required Energy Rating for a particular climate zone using house energy rating software or Elemental Provisions may be satisfied [17]. Building envelope construction types assessed in this study have been designed to meet Energy Efficiency Elemental Provisions. In climate zones 4-6, high mass materials (>220 kg/m^2) such as cavity brick and RE can be used without additional insulation so long as certain other requisites are met, e.g. glazing and shading requirements. If not high density, external walls must meet minimum R2.4 in climate zones 4 (hot dry summer, warm winter) and 5 (warm temperate) and R2.8 in climate zone 6 (mild temperate). For the purposes of this study, this is achieved using various thicknesses of glasswool insulation (GWI) with a density of 40 kg/m^3. Details of each envelope design are shown in Figure 1. Bricks were modelled as 110 mm commons, average of Midland Brick cored commons and Austral Bricks Standard 76.

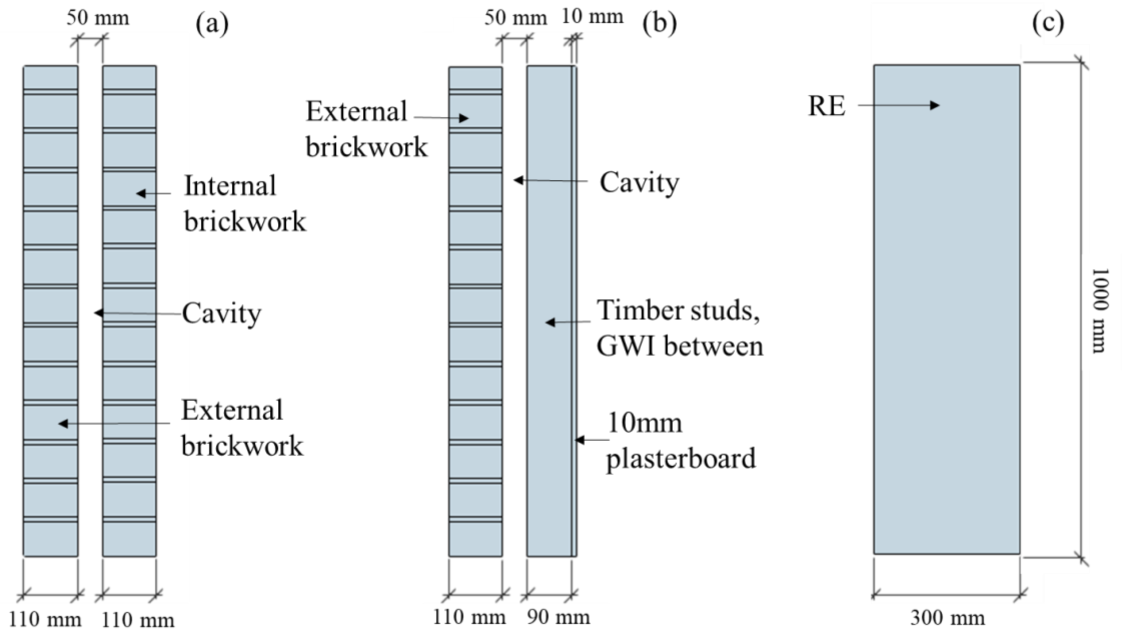

Figure 1: Cross-section of building envelope construction types; (a) cavity brick, (b) brick veneer, (c) rammed earth.

The boundary of the system studied is shown in Figure 2. Transport from plant to site has been excluded in the initial results as it is reasonably consistent regardless of material. A sensitivity study is conducted comparing different site locations. Construction energy has been excluded as it was found to negligible for RE in a previous study [18]. For consistency, brick veneer and cavity brick construction energies were also excluded. Operation stage was excluded in this assessment as thermal testing of the materials in question has not yet been completed.

The inventory is modelled based on EN 15804:2012+A1:2013 [15] which is predominantly an attributional approach. A cut-off system model is used meaning by-products were available burden-free at the primary production location. Transport and any processing required to prepare the by-product for the secondary material market is included. At end-of-life, the materials may be able to be recycled as aggregate however this stage has been excluded due to the uncertainty associated with long lifespan of a residential house, as the material properties at end of life are not known. Recycled content of materials has been included in the inputs to the model.

OpenLCA v1.7.2 software [19] using the AusLCI database v2.8 where possible [20] and Ecoinvent v3.4 where AusLCI data was unavailable [21] were used. Recycled brick and concrete were conservatively both included as recycled concrete aggregate. Brick's lower density would demand lower crushing energy. The environmental indicator category considered was global warming potential over 100 years (GWP100), developed by the Intergovernmental Panel for Climate Change [22]. This category measures emissions over a 100-year time period of any greenhouse gas, using CO_2 as an equivalence measure.

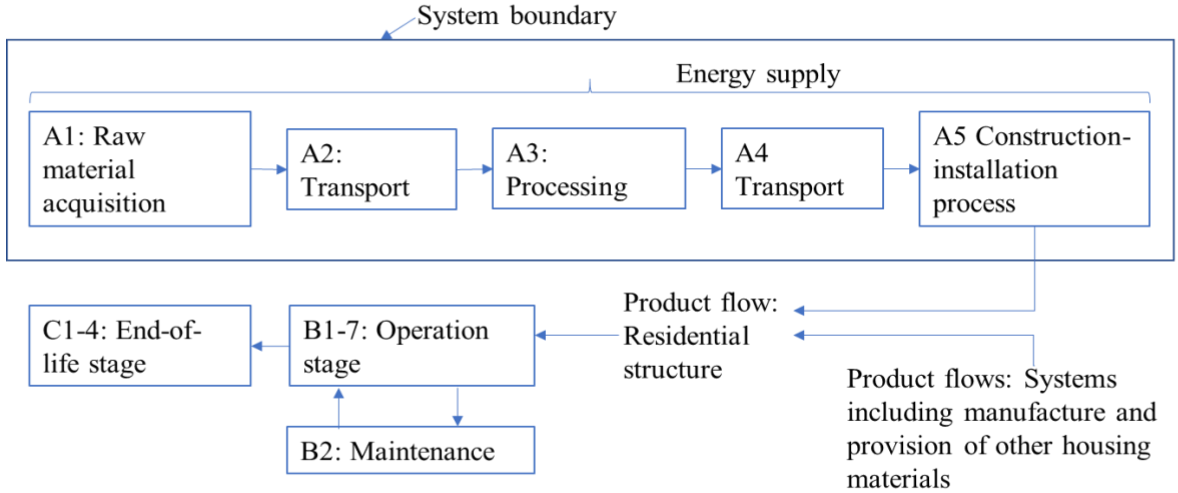

Figure 2: System boundary of RE LCA study, modules A1-5

3. Results and discussion

Figure 3 shows GWP100 (kg CO_{2eq}) for each material as a percentage of cavity brick emissions. These are a baseline measurement for each material/construction type: only required elements are included, e.g. bricks are unrendered/painted. Additional GWI required for brick veneer to meet R2.8 in climate zone 6 is shown separately to the GWI included to meet R2.4 in climate zones 4 and 5: the impact of additional insulation is minor compared to the total. For the three control materials, brick veneer, cavity brick and CL_C, the calcination process causes the vast majority of GHGE. For brick veneer and cavity brick, it is heating the kiln to fire the bricks that is responsible for GHGE whereas for cement production it is heating the kiln but also the inherent CO_2 released during clinker production, an intermediate product in production of cement:

$$CaCO_3 + heat \rightarrow CaO + CO_2 \text{ [23].} \quad (1)$$

As calcination is not required for any of the components of RE mixes that include industrial by-products, this significant emission step is avoided. Inclusions for by-products were any processing required to render the by-product useable for its purpose as the secondary material, e.g. grinding of blast furnace slag, plus transport from the primary producer to a metropolitan storage location.

Just over 50% of CL_AA and RBC_AA emissions are directly related to NaOH production. Bricks used for residential construction are typically specified to have a characteristic compressive strength of 12 MPa. CL_C has been designed to match this strength requirement. However, the newly developed mixes currently have varied 28-day UCS strengths, as marked on the Figure 3 secondary axis: CL_AA and RBC_AA are both significantly stronger than required, averaging 19.8 MPa and 24.1 MPa respectively. While it is known that strengths achieved by CSRE are directly related to cement content [24], future work by the authors will determine if this same relationship applies to these mixes. Given the contribution of NaOH to overall GWP, it is nevertheless reasonable to assume that materials with a smaller proportion NaOH, will have lower environmental impacts.

IOP Conf. Series: Earth and Environmental Science **323** (2019) 012143 doi:10.1088/1755-1315/323/1/012143

Based on the current mix, CL_AA, replacing cement with NaOH and industrial by-products, GWP is 60% lower than cavity brick and 40% lower than brick veneer. For the control RE mix, CL_C, GWP is 37% lower than cavity brick but only 8% lower than brick veneer due to the high emissions associated with cement production. This highlights that RE does not necessarily have significantly lower environmental impacts than 'business-as-usual' construction types but that this is highly dependent on stabiliser selection.

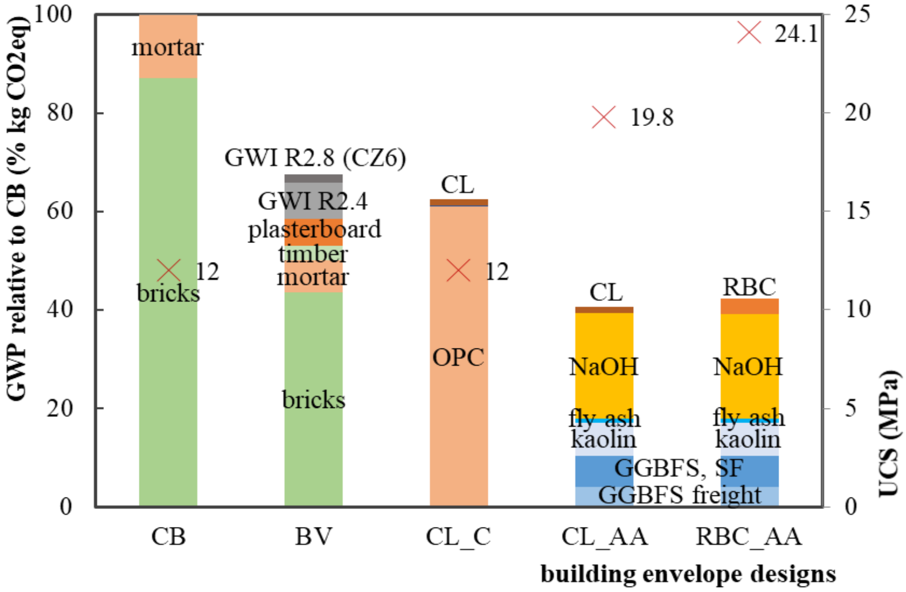

Figure 3: LCA results for environmental indicator category IPCC GWP for 1 m^2 of vertical external wall meeting insulation requirements for Australia's Climate Zones 4-6, system environment modules A1-3 only

Further to stabiliser selection, the base 'earth' component of a mix can also vary GWP of the final material. When comparing the two mixes CL_AA and RBC_AA, all components and proportions are identical other than base earth component. CL has low GWP as it is abundant around Perth, meaning transport distances are minimal, and it is a low density material so processing energy required is low. RBC, on the other hand, requires additional transport from demolition sites to processing locations, more varied sorting compared to the virgin CL, and additional processing energy as it is a higher density material. These factors result in a higher GWP for the fully recycled base earth compared to the virgin material for the same material mass. However, it should be noted that for the same mix proportions, RBC_AA has higher strength than CL_AA. Therefore, to achieve a given strength, less stabiliser should be required. As stabiliser contributes a much greater portion of the material's total GWP than earth, this will result in lower overall GWP. An additional benefit of using RBC over CL is its support of reusing waste materials to reduce use of virgin materials and reduce landfill, an OECD priority [3].

Another factor to consider in conducting LCA of RE is site location and transport requirements. Results of a sensitivity analysis addressing different transport requirements are shown in Figure 4. Two site locations are considered, 1) Perth metropolitan and 2) Kalgoorlie, a regional city 600km east of Perth. Two transport options are considered for Site 2:

i) all stabiliser materials transported from Perth, local material used as 'earth' component,
ii) all stabiliser and base earth materials transported from Perth.

It should be noted that, separate to these transport calculations, relevant freight to Perth metropolitan has already been included, e.g. fly ash includes 200 km transport in a 40T truck from coal plant location and GGBFS includes a portion of ship freight to account for imported material. GWP associated with material acquisition and production through to intermediate location in Perth metropolitan of RBC_AA materials are shown in Figure 4 to highlight impact of transport relative to total material impact.

IOP Conf. Series: Earth and Environmental Science **323** (2019) 012143 doi:10.1088/1755-1315/323/1/012143

Site 1 conservatively assumes a delivery location of 50 km in metropolitan Perth for all materials, based on location of material storage and processing locations around Perth. When stabiliser materials (NaOH and aluminosilicates) are transported from Perth to the site in Kalgoorlie, this adds 3.6 kg CO_{2eq} or 10% in the case of this mix for the FU of 1 m^2 vertical wall. If all materials, including base earth material, are transported from Perth, transport impacts increase significantly due to the mass of the earth component. In the case of RBC_AA, transport adds a further 60% on top of the material impacts considering a site within Perth. Local earth material in a regional location such as Kalgoorlie could include a local virgin material or local recycled materials so long as the location has the capacity to process the materials e.g. to crush recycled brick. Any local soil would require testing to establish whether it was appropriate to be used as a RE base. This potential to use local materials for the bulk of wall mass increases the benefit of these RE mixes relative to more standard building materials if components of these require transport to regional locations.

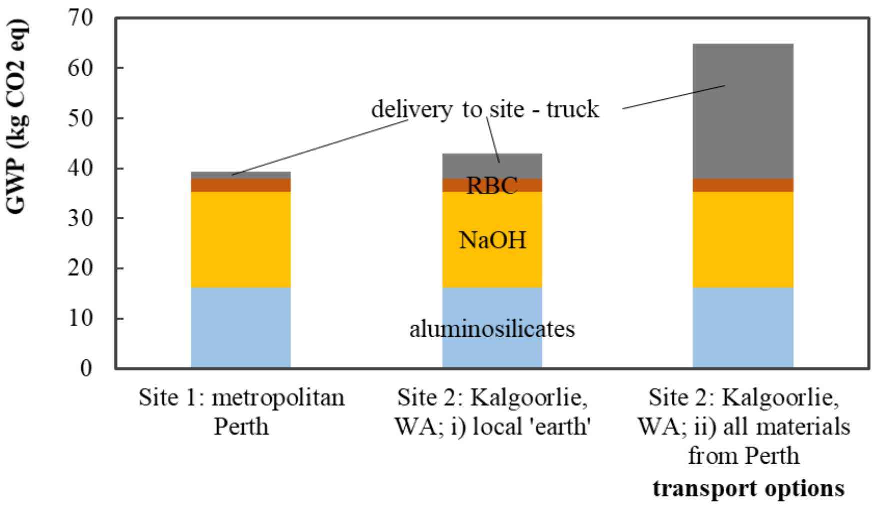

Figure 4: Varying site location and/or delivery requirements, mix: RBC_AA

4. Conclusions

The aim of this paper was to assess GWP of RE materials using LCA and determine whether use of these materials may provide a benefit over use of more common building materials. Results show that use of RE mixes stabilised with aluminosilicate by-products and NaOH would reduce GWP by 60% compared to cavity brick for the same unit of external wall and by 40% compared to brick veneer.

The newly developed alkaline activated RE mixes have a GWP 30-40% lower than the current most common RE variety in WA, CL_C, highlighting the benefits of using alternatives to cement in RE construction. Nevertheless, given the most prevalent construction type in Perth, WA is cavity brick, RE stabilised with cement is still a significantly better alternative in terms of reducing GHGE.

If the construction site is in a regional location, maintaining the benefit of using any RE mix is contingent on ability to use local materials, virgin or recycled, as the base ‘earth’ component. The high mass of base material required means GHGE emissions associated with long transport distances are high. Where possible, use of recycled materials as the base material has the benefit of supporting waste reuse, a current government and OECD priority.

Valuable further work would include thermal analyses of the mixes studied here as well as others to determine variability according to mix design, i.e. to what degree thermal properties are controlled by variables such as wall thickness and density rather than exact components and proportions. Thermal testing, i.e. determination of resistance to heat flow (R-value), would allow for comparison of GWP based on FU having identical R-values as well as wall designs meeting the current NCC requirements. Air quality tests of indoor environments created by these materials would also be beneficial. Lastly, analysis of materials at end-of-life would better enable understanding of capacity for reuse and/or recycling. This data could then be used for a more complete LCA of the full life cycle.

Acknowledgements

The authors thank Tim Grant of Lifecycles for having provided advice and assistance that was invaluable in completing the LCA. The authors wish to acknowledge Josh Galvin, Max Hoy, Joel Bonsel, Paul Shaw, Matt Noack and Jing Bong for their contributions to the laboratory work. We also thank Sarah Lumley, Chris Beckett and Rupert Myers for guidance, and Daniel Sly and Emily Meek for proofreading.

Funding: This study was supported by the University of Western Australia Hackett Postgraduate Research Scholarship, the University of Western Australia Graduate Research School Travel Award, and the University of Western Australia Postgraduate Students' Association Fieldwork Grant.

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