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IMPROVING RAMMED EARTH WALLS' SUSTAINABILITY THROUGH LIFE CYCLE ASSESSMENT (LCA)

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Abstract

Rammed earth, an ancient construction technique based on compacting soil in progressive layers into formwork, has recently seen renewed interest due to its low environmental impact compared to traditional wall systems. However, the choice of soil and the addition of stabilisers to improve material durability and strength could jeopardize these environmental benefits. The focus of this paper is the lifecycle environmental impact of a typical rammed earth wall in Perth, Western Australia. The goal is to estimate variation in the structure's sustainability according to the materials used. Several soil mixtures, conventional and innovative ones, as well as recycled and waste materials (e.g. recycled concrete, fly ash and carbide lime) were considered for the analysis. Durability tests were performed to compare specimens' mechanical performance and their resistance to erosion. The sustainability analysis of the building material is therefore extended from the construction phase to the entire lifecycle, as recommended by the LCA standards. Results indicated that the choice of the mixture's components and their source could significantly affect the overall environmental performance of the structure. Even though every soil has different characteristics, materials similar to the ones considered here could be sourced anywhere and the results could be adapted to different geographical areas.

Keywords:

rammed earth; LCA; sustainable building materials; durability; waste materials

1 INTRODUCTION

Rammed Earth (RE) is an ancient construction technique based on the compaction of soil in progressive layers into formwork. The perception that the use of natural materials is environmentally benign has led to a renaissance of this building technique. Soil traditionally used for RE buildings is unstabilised and has an adequate proportion of inert aggregate fraction (sand and gravel) and a binder fraction (silt and clay) [1]. Nowadays, stabilisers are generally added to the earth mixture to improve the wall strength and the resistance to erosion. The incorporation of Portland cement is very common in Australia, where stabilised RE housing has gained popularity in recent years. However, cement stabilisation reduces the sustainability of RE buildings [2-4] and alternative stabilisers have been tested in the past decades. The main alternative to cement is lime, but the use of waste materials, biopolymers, geopolymers and fibres have been investigated as well in the literature (e.g. [5-7]). Most of these studies focus on the mechanical properties of innovative mixtures; even though durability is a main concern for earthen structures [8, 9], it is often not considered together with their environmental performance. In this paper, the lifecycle assessment (LCA) tool is applied to a construction site in Perth, Western Australia (WA), to assess both the environmental performance *and* the durability properties of different stabilised RE mixtures. Results are used to understand whether, in a lifecycle perspective, a longer lifespan of the structure and lower maintenance costs could offset the higher environmental impacts in the construction phase.

2 MATERIALS AND METHODS

2.1 Materials

Natural soil is very rarely used in Perth metropolitan area for RE construction, due to its poor grading. Crushed limestone sourced by a local quarry has been adopted, instead, as an alternative artificial soil for RE purposes by RE practitioners in Perth in the last 30 years. It is predominantly used with Portland cement, 5 to 15% by mass of dry crushed limestone. Although crushed limestone is advantageous in terms of consistency and hence quality control, its use entails several environmental impacts arising from the excavation process, the crushing of the rock and the final transport. Here, we study alternative soil mixes in addition to the base case of cement-stabilised crushed limestone.

Local Soil (LS)

Local soil (LS) is used in other locations of WA than Perth metropolitan area, where remoteness or lack of quarries make it the only available building material. In the present work we studied the feasibility of using LS obtained from the excavation site of a RE building under construction in Perth metropolitan area. The Particle Size Distribution (PSD) of the local soil showed, as expected, that 96% of the material falls within the sand range (*Figure 1*). The curve does not match the recommendations made in [10] for the selection of a suitable soil for RE construction. In order to use the local soil, both fine particles (binders and/or fillers) and inert fraction bigger than sand (i.e. gravel) had to be added. The resulting “engineered local soil” (ELS) comprised 60% LS, 30% clayey soil (from a quarry situated ca. 130 km away from the LS building site) and 10% gravel (quarry ca. 60 km distant). The PSD of the ELS is shown in *Figure 1*.

Waste materials

Several waste materials were considered in this study:

- Recycled Concrete Aggregate (RCA): inert material obtained from the demolition of disused concrete structures in Perth area. The Particle Size Distribution (PSD) obtained by dry sieving is shown in *Figure 1*.
- Class F Fly Ash (FA): residue generated by the combustion of coal in a power station located ca. 200 km away from the considered building site. A chemical analysis has shown that the FA is 58.7% SiO_2, 27.4% Al_2O_3, 8.1% Fe_2O_3, 1.6% TiO_2 and 0.9% CaO.
- Carbide Lime (CL): by-product of the generation of acetylene gas through the hydrolysis of calcium carbide. CL is generated as an aqueous slurry and is composed essentially by calcium hydroxide with minor parts of calcium carbonate, unreacted carbon and silicates. The distance between the acetylene gas production site and the construction site is ca. 20 km.

Mixtures overview

Mixes (soil material and stabiliser) used in this study are referred to by the following numbers:

0. Crushed limestone + 10 %* cement
1. RCA + 10% cement
2. RCA + 5% cement + 5% FA
3. ELS + 5% cement + 5% FA
4. ELS + 5% CL + 25% FA
5. ELS

* “%” refers to the percentage of dry soil

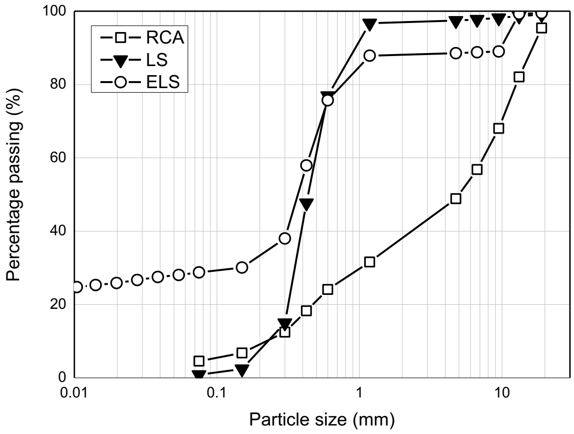

Figure 1: Particle Size Distributions for RCA, LS and ELS.

2.2 LCA

Methodology

The LCA presented in this paper follows the methodology defined by international norms: ISO 14040 [11] and ISO 14044 [12]. The software SimaPro 8.0.5 was used for the analysis implementation. When waste materials were used in the mixture, neither associated environmental impacts nor benefits were considered. Impacts related to raw material extraction and processing were extrapolated from the Ecoinvent database [13] and the Australasian LCA database [14].

Functional Unit

The functional unit considered was the square meter of RE wall. The thickness of the wall considered was 300 mm, which is typical for most RE structures.

System boundaries and data quality

The processes considered for the study were:

- Raw material extraction
- Production of mixtures’ elements
- Transport of materials to construction site

Since the goal of the study was to compare different mixtures, processes of the wall’s lifecycle independent from the earth mixture were not considered (e.g. materials and machinery used for the wall's erection). As no real case has been found using the same mixtures considered in the study, energy for mixing and for ramming were not included. Further investigation is required to understand how these energies would affect the different mixtures' sustainability. However, in [4] it was concluded that energy expenditure in the compaction process is negligible when compared to energy content of cement. Furthermore, since the focus of this study is limited to the RE component alone, the operational phase of the building (i.e. heating and cooling) was excluded from the study. The choice of the mixture, however, could affect the hygrothermal behaviour of the wall and consequently the energy requirements to reach the comfort of the building's occupants. How the different mixtures affect the overall sustainability of the building will be the focus of a subsequent paper. The end of life of the wall, difficult to forecast, was not included in the assessment.

Impact indicators

Two midpoint indicators were considered in the study: CML-IA Baseline (characterization factors developed by the University of Leiden) and Cumulative Energy Demand (CED [13]).

2.3 Durability tests

Durability tests allows to include the use phase in the sustainability evaluation of the wall. Since no internationally recognized standard to assess RE's durability is available, several different tests were performed to assess the durability behaviour of the earth mixtures.

Accelerated Erosion Test

The test consisted of spraying the face of a sample for a period of one hour or until the jet of water spray completely penetrated the sample. The exposed surface was a circular area of 150 mm diameter and the jet of water, projecting at 50 kPa, was placed 470 mm from the sample. The maximum permissible erosion rate for all types of earth construction is one mm per minute [15].

Modified Wire Brush Test

This test, as presented in *ASTM D559-03* [16], was developed to evaluate the durability of soil-cement mixtures. It determines weight loss, water content change, and volume change (swell and shrinkage) produced by repeated wetting and drying (12 cycles) of compacted specimens. The test has similar conditions to heavy driving rain. Fitzmaurice [17] proposed a weight loss limit of 5% for Compressed Earth Blocks in regions with rainfall greater than 500 mm and 10% otherwise. Some modifications were made to the original test in order to have more representative results.

Unconfined Compressive Strength (UCS)

Even though UCS is not a durability parameter, its assessment gives information on the overall material mechanical performance. Moreover, NZS 4298 sets an UCS limit (1.3 MPa) for earthen construction [18]. All specimens (Ø100 × 200mm cylinders) were cured for 28 days in a room at constant high humidity (RH: 96±2%) and moderate temperature (21±1°C) before testing.

3 RESULTS AND DISCUSSION

3.1 LCA

CML-IA Baseline

CML-IA Baseline results are presented in *Figure 2.* The phases considered were the extraction and processing of the mixture base components and their transport to the construction site. The studied construction site was located in the centre of Perth. Results show that all mixes were better than the base case (Mix 0) for all the environmental impact categories studied. The impacts related to all the categories, in particular to global warming (see Global Warming Potential (GWP) columns in *Figure 2*), decreased with the reduction of cement in the mixture. Emissions generated in the clinker production process were the main contributor for all the impact categories except for abiotic depletion, whose main impacts were related to the consumption of chrome in the plating of the steel used in the cement factory and the lead used in the gypsum production process.

When considering the inert fraction, if the binding properties of clay are not required (due to stabilisation), the best environmental solution is to use RCA, which is free of the impacts related to raw material extraction. Using crushed limestone instead of the engineered soil mixture improved performance in all the environmental impact categories, except for the eutrophication and the acidification, because of the shorter distance to the building site of the limestone quarry compared to that of the clay source. Eutrophication and acidification's impacts results are higher because of the emissions generated from the limestone rock blasting process. Nevertheless, if clay's binding properties are not required, recycled fine particles or fillers from closer quarries could be used to drastically reduce the environmental impacts of the mix. On the other hand, clay guarantees binding properties that could reduce the need of cement and lead to better environmental performance. Using RCA (Mix 2) instead of engineered soil (Mix 3) with the same rate of cement stabilisation led to a reduction of 12% in terms of GWP. Using engineered soil with alternative stabilizers (Mix 4) or no stabilisers at all (Mix 5) led to a reduction, compared to the same engineered soil stabilised with cement (Mix 3), of 78% and 83% respectively, always in terms of GWP. The difference would be even greater if cement stabilisation was higher than the 5% (the

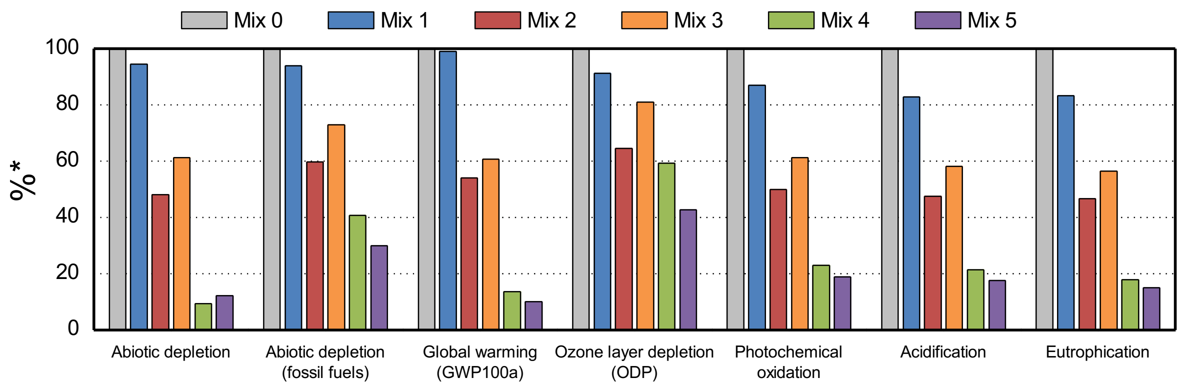

*Figure 2: CML-IA results (*percentage is normalized to the max reached in each impact category).*

minimum typically used for RE construction) considered in Mix 3.

Cumulative Energy Demand (CED)

CED results are reported in *Figure 3*. The main contributor for all mixes was the embodied energy of the fossil fuels used both for sintering the clinker and for fuelling the vehicles to transport the materials. Results are therefore consistent with the CML's impact category Fossil Fuels Depletion (see *Figure 2*). The renewable contribution to the wall's energy demand was very low and derives from the renewable component of the Australian electricity production mix.

3.2 Durability tests

Accelerated Erosion Test (AET)

Mix 1, Mix 2 and Mix 4 had no visible erosion after one hour. Mix 3 had some minimal localized erosion. Mix 5 was completely penetrated after 40 minutes. All mixes except Mix 5 passed the test.

Modified Wire Brush Test (MWBT)

All mixes except Mix 5 (not tested because it would not have resisted a prolonged submersion in water) responded well to the test: all specimens had very low mass losses (lower than 5%), no volume expansion and small increase in water absorption.

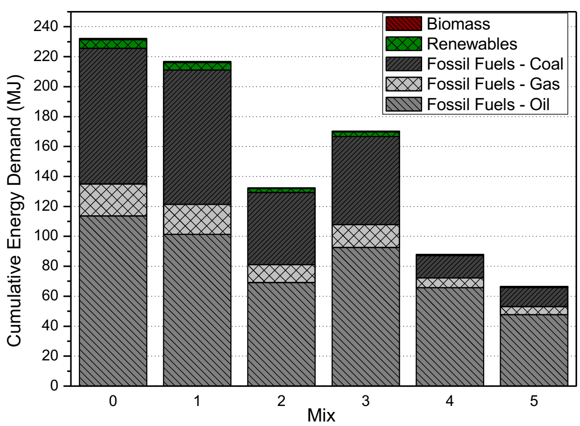

Figure 3: CED results.

Mix	AET	MWBT	UCS
0	n.a.*	n.a.	13.8 MPa [19]
1	pass	pass	8.7 MPa
2	pass	pass	6.7 MPa
3	pass	pass	5.4 MPa
4	pass	pass	2.8 MPa
5	fail	fail	1.3 MPa

*Table 1: durability tests results (*n.a.: not available).*

Unconfined Compressive Strength (UCS)

The results reported in *Table 1* show a reduction of the compressive strength from the base case (highest UCS) to Mix 5 (lowest UCS). According to the results, when cement is used as stabiliser, the use of crushed limestone as base component for the mixture guarantees better mechanical performances than using RCA or the engineered soil. Halving the amount of cement and substituting the part removed with FA led to a UCS reduction of about 23%. The complete elimination of cement and its substitution with CL and FA (Mix 4) led to a significant reduction in UCS, but results remained higher than the limits set by NZS 4298. The UCS of the unstabilised soil (Mix 5) is equal to the NZS limit.

4 CONCLUSIONS

- The waste soil gathered from the building foundation's excavation could not be used to make the RE walls due to its poor grading. However, with the addition of the recommended amount of fine and coarse particles, the soil could be used as a base for the RE mixture. The environmental benefits of using the waste soil depend on the amount of material collected, subject to the foundation depth, and especially on proximity of sources of fine and course particles; if these sources are far from the building site the environmental benefits could be offset.

- The use of alternative stabilisers had a far higher impact in the reduction of the environmental cost than the impact generated by the alternative choice of aggregates.
- Unstabilised RE (Mix 5) had poor durability test results, although it achieved the minimum UCS required by NZS 4298 for earthen structures. To improve the durability of this mixture, avoiding the use of stabilisers, a sloping roof could be employed (to prevent directly impacting rainfall).
- Among the mixes tested, Mix 4 was very promising. The use of carbide lime and fly ash to stabilise the soil led to a drastic reduction of the environmental impacts, in particular the GWP, in comparison to the base case. Even though the mix has a reduction of 80% in term of UCS, UCS was still adequate to guarantee a safe structural capacity. Mix 4 exhibited good durability properties.
- The choice of the mixture could lead to a variation of the hygrothermal behaviour of the wall. How these changes would affect the environmental impacts of the operational phase of the building (i.e. heating and cooling) will be the discussion topic of a subsequent paper.

5 SUMMARY

RE mixtures in WA are generally stabilised with cement to increase their mechanical performances. The goal of this study was to find a sustainable alternative to cement for RE stabilisation. The use of waste and local materials could lead to better environmental performance whilst guaranteeing sufficient mechanical and durability properties.

6 ACKNOWLEDGMENTS

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7 REFERENCES

1. Minke, G., *Building with Earth: Design and Technology of a Sustainable Architecture*. 2006: Birkhäuser.

2. Owen, C., G.J. Treloar, and R. Fay. *Embodied energy assessment of rammed earth*. in *SOLAR '99 Conference: Opportunities in a Competitive Marketplace*. 1999. Geelong.

3. Maskell, D., A. Heath, and P. Walker, *Comparing the Environmental Impact of Stabilisers for Unfired Earth Construction.* Key Engineering Materials, 2014. **600**: p. 132-143.

4. Venkatarama Reddy, B.V. and P. Prasanna Kumar, *Embodied energy in cement stabilised rammed earth walls.* Energy and Buildings, 2010. **42**(3): p. 380-385.

5. Ciancio, D., C.T.S. Beckett, and J.A.H. Carraro, *Optimum lime content identification for lime-stabilised rammed earth.* Construction and Building Materials, 2014. **53**: p. 59-65.

6. Eires, R., *Construção em Terra: Desempenho melhorado com incorporação de biopolímeros (Building with earth: improved performance with biopolymers incorporation)*. 2012, University of Minho: Guimarães.

7. Pflughoeft-Hassett, D.F., et al., *Use of bottom ash and fly ash in rammed-earth construction*. 2000, University of North Dakota.

8. Morel, J.-C., Q.-B. Bui, and E. Hamard, *Weathering and durability of earthen materials and structures*, in *Modern earth building*. 2012, Woodhead Publishing Limited. p. 282-303.

9. Heathcote, K.A., *Durability of earthwall buildings.* Construction and Building Materials, 1995. **9**(3): p. 185-189.

10. Houben, H. and H. Guillaud, *Earth Construction: A Comprehensive Guide*. 1994.

11. ISO, *ISO 14040:2006 Environmental management -- Life cycle assessment -- Principles and framework*. 2006.

12. ISO, *ISO 14044:2006 Environmental management -- Life cycle assessment -- Requirements and guidelines*. 2006.

13. Weidema, B.P., et al., *The ecoinvent database: Overview and methodology, Data quality guideline for the ecoinvent database version 3, ,* www.ecoinvent.org. 2013.

14. *Australian LCA database (Version 2015.02) developed from 1998 up to 2007 by Centre for Design from data originally developed with the CRC for Waste Management and Pollution Control as part of an Australian Inventory data project.* 2015.

15. Middleton, G.F., *Bulletin 5 - Earth Wall Construction*. 1987, National Building Technology Centre: Chatswood (Australia).

16. ASTM, *ASTM D559-03 Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures*. 1989.

17. Fitzmaurice, R., *Manual on Stabilised Soil Construction for Housing*. 1958, New York: Technical Assistance Programme, United Nations.

18. Standards New Zealand, *NZS 4298: 1998 Materials and workmanship for earth buildings.* 1998: Wellington, New Zealand.

19. Ciancio, D. and J. Gibbings, *Experimental investigation on the compressive strength of cored*

and molded cement-stabilized rammed earth samples. Construction and Building Materials, 2012. **28**(1): p. 294-304.