IMPROVING RAMMED EARTH BUILDINGS' 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 the soil and the addition of stabilisers to improve material durability and strength could jeopardize these environmental benefits. Stabilizing earth is very common in Australia, where rammed earth housing accounts for an important share of the new build market.
The focus of this paper is the lifecycle environmental impact of a typical rammed earth building 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 specimen's 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, similar materials 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 led to a renaissance of this building technique. The 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 [2, 3]. The incorporation of Portland cement is very common in Australia, where RE housing accounts for an important share of the new build market. However, cement stabilisation is believed to reduce the sustainability of RE buildings and alternative stabilisers have been tested in the past decades [3-6]. The main alternative to cement is lime [1, 7, 8], but the use of waste materials (e.g. fly ash [9-11], rice husk ash [6, 12], ground granulated blast furnace slag [13], used cooking oil [8], carbide lime [14]), biopolymers [8] (e.g. blood [15], corn starch, wheat flour, sugar, linseed oil, glycerol, casein), geopolymers [8, 10] (e.g. sodium hydroxide, sodium silicate, calcium chloride, sodium chloride, sodium borate) and fibres (e.g. jute fabric [16]) have been investigated as well. Most of these studies focus on the mechanical properties of the innovative mixture; even though durability is a main concern for earthen structures [17-20], 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 mechanical properties of different stabilised RE mixtures. Results are used to provide suggestions on how to improve the sustainability of new RE buildings.

2 MATERIALS AND METHODS

2.1 Materials

RE construction in metropolitan Perth, WA, predominantly uses a mixture of Portland cement (5 to 15% by mass) and crushed limestone as the base material. However, an advantage of the RE technique is that many soil types can be used, depending on availability. Here, we study several soils in addition to this base case to investigate stabiliser suitability for a broad range of construction scenarios.

Local soil

Local soil is very rarely used for RE construction in Perth, due to its poor grading and a history, and so accumulated experience, of building with crushed limestone. However, local soil is used in interior WA, and in many other places around the world, where the grading is improved. In the present work we studied the feasibility of using local soil for RE buildings. Local soil was obtained from the proposed construction site during foundation excavation.

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 the 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 stabilizer) used in this study are referred to by mix number as follows:

0. Crushed limestone + 10 % cement (base case scenario)
1. RCA + 10% cement
2. RCA + 5% cement + 5% FA
3. Soil + 5% cement + 5% FA
4. Soil + 5% CL + 25% FA
5. Soil

2.2 LCA

Methodology

The LCA presented in this paper follows the methodology defined by international and European norms: ISO 14040 [21], ISO 14044 [22] and EN 15804 [23]. 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 [24] and the Australasian LCA database [25].

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 [5] it was concluded that energy expenditure in the compaction process is negligible when compared to energy content of the cement. The end of life of the wall is difficult to forecast and therefore it was not considered.

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).

2.3 Durability tests

Durability tests extend the sustainability evaluation of the wall to the use phase. Since no internationally recognized standard to assess RE's durability is available, several different tests were performed to understand the durability behavior 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 sample was penetrated. The exposed surface was a circle 150 mm in 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 [26].

Modified Wire Brush Test

The test [27], developed to evaluate the durability of soil-cement mixtures, 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 [28] 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

Even though UCS is not a proper durability test, the test gives information on material mechanical performance. Moreover, NZS 4298 sets a UCS limit (1.3 MPa) for earthen construction [29]. 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 Soil suitability

The PSD of the local soil showed that 96% of the material falls within the sand range (*Figure 1*). The curve does not match the recommendations made in [30] 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 soil" comprised 60% local soil, 30% clayey soil (from a quarry situated ca. 130 km away from the building site) and 10% gravel (cave ca. 60 km distant) was thus used as base mixture for Mixes 3, 4 and 5. The PSD of the engineered soil is shown in *Figure 1*.

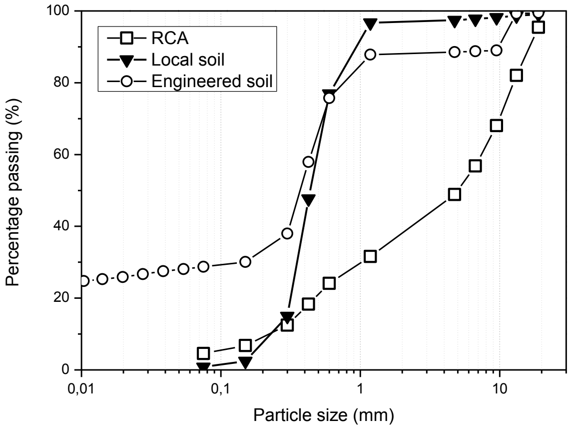

Figure 1: Particle Size Distributions for the local soil and engineered soil (Mix 5)

3.2 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 construction site considered was located in the center 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 stabilization), 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. Eutrophication and acidification's impacts results are higher because of the emissions generated from the limestone rock blasting process.

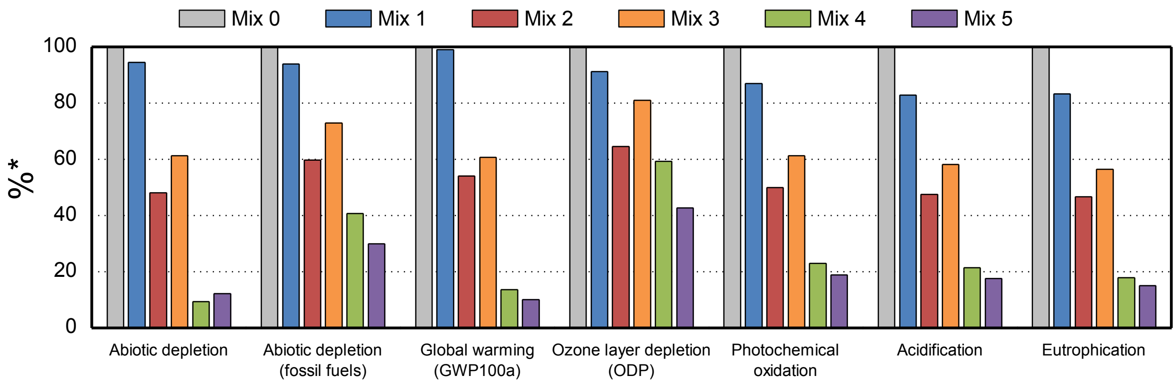

*Figure 2: CML-IA results (*percentage is normalized to the max reached in each impact category)*

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 make the use of cement unnecessary and lead to much better environmental performance. Using RCA (Mix 2) instead of engineered soil (Mix 3) with the same rate of cement stabilization led to a reduction of 12% in terms of GWP. Using engineered soil with alternative stabilizers (Mix 4) or no stabilizers at all (Mix 5) led to a reduction, compared to the same engineered soil stabilized with cement (Mix 3), of 78% and 83% respectively, always in terms of GWP. The difference would be even greater if cement stabilization was higher than the 5% (the minimum typically used for RE construction) considered in Mix 3.

Cumulative Energy Demand

CED results are reported in **Errore. L'origine riferimento non è stata trovata.**. The main contributor for all mixes was the embodied energy of the fossil fuels used both for sintering the clinker and for fueling the vehicles to transport the materials. Results are therefore consistent with the CML's impact category Fossil Fuels Depletion (see *Figure 2*). The renewable

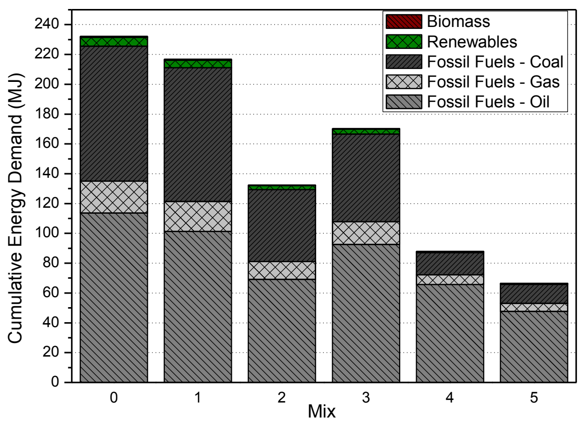

Figure 3: CED results

contribution to the wall's energy demand was very low and derives from the renewable component of the Australian electricity production mix.

3.3 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. Even though every specimen passed the test, a variation in the quality of the specimens' manufacture led to significantly different results.

Table 1: durability tests results

Mix	AET	MWBT	UCS
0	n.a.	n.a.	13.8 MPa [31]
1	v	v	8.7 MPa
2	v	v	6.7 MPa
3	v	v	5.4 MPa
4	v	v	2.8 MPa
5	x	x	1.3 MPa

Unconfined Compressive Strength (UCS)

The results, reported in **Errore. L'origine riferimento non è stata trovata.**, show a reduction of the compressive strength from the base case (highest UCS) to Mix 5 (lowest UCS). The results show that the use of crushed limestone as base component for the mixture and cement as stabiliser 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 quarry proximity; if quarries are far from the building site the environmental benefits could be offset.
- The use of alternative stabilizers, or not using stabilizers at all, led to a reduction of the environmental burden of an order much higher than the difference related to the choice of the aggregates.
- Unstabilised RE 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 stabilizers, 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 sufficient and it exhibited good durability properties.

5 SUMMARY

RE mixtures in WA are generally stabilised with cement to increase their mechanical performances. The goal of the 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.

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