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Life cycle analysis of environmental impact vs. durability of stabilised rammed earth

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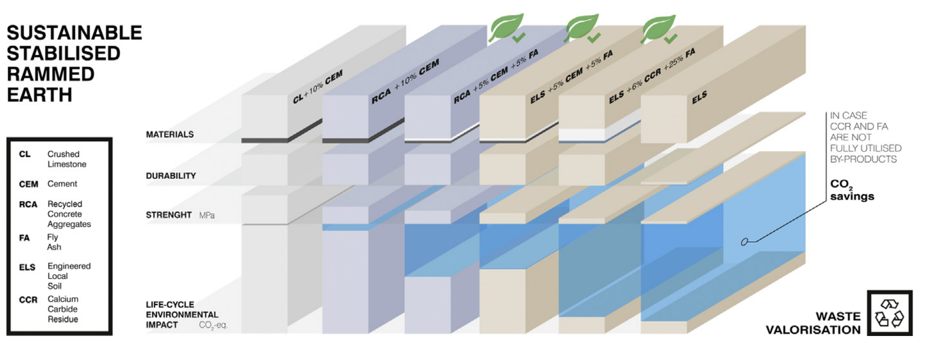
HIGHLIGHTS

- Reducing cement content in SRE results in considerable emissions and energy savings.
- The use of waste materials is recommended to reduce the environmental impact of SRE.
- Consequential LCA results depend on the marketability of the by-product used.
- It is possible to have durable, strong and environmentally sustainable SRE mixes.
- Unconfined compressive strength should not be used as an indicator of durability.

GRAPHICAL ABSTRACT



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ABSTRACT

Rammed earth (RE) has enjoyed a revival in recent decades due to the increasing awareness of environmental issues surrounding the building industry. Although RE in its traditional form is deemed a highly environmentally-friendly material, the same cannot be said for its modern stabilised counterpart. Comprehensive experimental procedures exist to estimate mechanical strength properties of stabilised RE (SRE). However, tests for material durability are far less common. Engineers and practitioners therefore assume that strength and durability are interchangeable properties, i.e. the stronger the material, the more durable. Inflated strengths are recommended to ensure adequate durability, leading to high environmental costs through excessive use of stabilisers.

This paper rates the relevance of two acknowledged durability tests (accelerated erosion due to sprayed water and mass loss due to wire brushing) and relates outcomes to the strength and the environmental impact of several SRE mixes. The environmental impact of each mix was estimated using attributional and consequential life cycle assessment (LCA) approaches as well as an assessment of cumulative energy demand. Results demonstrated that it is possible to have durable SRE mixes without paying the cost of using environmentally-expensive stabilisers.

Abbreviations: ADP elements, abiotic resource depletion potential for elements; ADP fossil fuels, abiotic resource depletion potential of fossil fuels; AET, accelerated erosion test; ALCA, attributional LCA; AP, acidification potential of land and water; CCR, calcium carbide residue; CED, cumulative energy demand; CL, crushed limestone; CML, Institute of Environmental Sciences, Leiden University; CLCA, consequential LCA; ELS, engineered local soil; EP, eutrophication potential; FA, fly ash; FU, functional unit; GWP, global warming potential over 100 years; LCA, life cycle assessment; LCI, life cycle inventory; LS, local soil; MDD, Maximum Dry Density; MPT, Modified Proctor Test; ODP, stratospheric ozone layer depletion potential; OWC, Optimum Water Content; POCP, tropospheric ozone photochemical oxidants formation potential; PSD, particle size distribution; RCA, recycled concrete aggregates; RE, rammed earth; SRE, stabilised rammed earth; UCS, unconfined compressive strength; WA, Western Australia; WBT, wire brush test.

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1. Introduction

Rammed earth (RE) is a very old construction technique that has recently experienced a revival around world due to its appealing environmental features [1]. The traditional form of RE consists of moist loose soil that is compacted inside formwork in layers to create load bearing walls. Removing the formwork permits the wall to dry: a process through which it gains its structural integrity [2]. Traditional RE soil mixes must be well-assessed to optimise strength and not all soils are suitable for RE construction [3]. Even so, the compressive strength of such suitable mixes is usually only in the range of 0.5–2.5 MPa [4,5].

Walls made of traditional (or unstabilised) RE can be damaged if not properly protected from wind and rain [6]. Erosion and water intrusion can lead to dust and sometimes cracking. The use of additives, such as quicklime and biopolymers, to improve the resistance of RE can be traced back centuries [7,8] and is now a common practice in several countries around the world. Stabilised rammed earth (SRE) is based on the same construction method, i.e. moist loose soil compacted inside formwork, but the soil mix is stabilised with (most commonly) cement or lime. Cement and lime not only enhance strength but they also reduce the tendency to swell and shrink, to crack and to generate dust [9,10]. In other words, even though traditional RE is characterised by the use of raw minerals with minimal embodied energy (i.e. the total energy required for the materials' production) [11], the structure is susceptible to damage and requires a significant amount of (human) energy to be spent on maintenance and repair. On the other hand, SRE requires less maintenance once erected. This, however, comes with an environmental cost: first of all, cement manufacturing is responsible for high CO_2 emissions; secondly, although traditional RE has the potential to use zero transport energy (presuming that the soil available on the construction site is suitable), stabilisers must be transported from the nearest batching plant to the construction site [12,13]. This argument motivated the research presented in this paper: assessing the life cycle environmental impact of SRE by taking into account its embodied energy, mechanical strength and durability. Six mixes, representing a range of potential construction materials from natural soil to a quarried product, were investigated, stabilised with traditional (i.e. cement) and innovative binding agents (i.e. calcium carbide residue and fly ash). Natural soil was obtained from a construction site in Perth, Western Australia (WA), where a new SRE house was to be built. This house was used as the basis for the environmental life cycle assessment, examining the impact each mix's use would have had on the environmental performance of the SRE walls. Material mechanical performance was assessed via compressive strength testing and durability via accelerated erosion and wire brush testing.

2. Materials

The six mixes investigated in this study were chosen to represent a range of potential RE construction scenarios in Perth, WA. The first mix consisted of crushed limestone (CL) stabilised with 10% Portland cement by mass of dry substrate (henceforth, "cement" refers to Portland cement). This solution is extensively adopted in Perth due to the poor suitability of the local soil for SRE construction and because CL has proven to reliably provide consistent aesthetic and mechanical performance. It is usually stabilised with 7–15% cement by mass of dry CL. CL SRE was used during construction of the house used in this work as a case study. Hence, CL SRE is considered to be a 'base case' for comparative purposes.

The second and third mixes represented a solution that has gained increasing popularity in Perth over the last 5–10 years. The main component of these mixes is a blend of recycled concrete aggregates (RCA), an inert material obtained from the demolition of disused concrete structures. In this study, the second mix is RCA stabilised with 10% cement. The third mix is RCA stabilised with 5% cement and 5% fly ash (FA), a residue generated by coal combustion. FA used in this study was obtained from a power station located ca. 200 km from the construction site. Chemical analysis showed that the FA comprised 58.7% SiO_2, 27.4% Al_2O_3, 8.1% Fe_2O_3, 1.6% TiO_2 and 0.9% CaO.

The remaining mixes (Nos. 4, 5 and 6) were based on the local soil (LS) available at the construction site. Due to the poor grading (i.e. sand for the vast majority) and the lack of clay, LS was not suitable for RE purposes in its natural state and it would have been disposed of or used in landscaping under normal circumstances. LS grading and compactability were improved by adding fine (binders and/or fillers) and coarse particles (i.e. gravel) to the raw material. The resulting "engineered local soil" (ELS) comprised 60% LS, 30% clayey soil (from a quarry situated ca. 130 km from the construction site) and 10% gravel (quarry ca. 60 km away). Mix 4 was ELS stabilised with 5% cement and 5% FA, as per Mix 3. Mix 5 was ELS stabilised with 6% of calcium carbide residue (CCR), also known as carbide lime, and 25% FA. CCR is a by-product of acetylene gas generation through the hydrolysis of calcium carbide. It is generated as an aqueous slurry and essentially comprises calcium hydroxide with minor parts of calcium carbonate, unreacted carbon and silicates. The distance between the acetylene gas production site and the construction site was ca. 20 km. Mix 6 was unstabilised ELS. A summary of all mixes is given in Table 1. Extensive microstructural investigations of Mixes 4, 5 and 6 were presented by the authors in [14,15]. CL, RCA and ELS particle size distributions (PSDs) are presented in Fig. 1.

3. Experimental procedures

The optimum water content (OWC) and the maximum dry density (MDD) of each mix were calculated using the modified Proctor test (MPT). All compaction tests followed wetting and mixing procedures given in AS 1289.5.2.1 [16] for unstabilised material and [17] when stabilisers were present. OWC and MDD values are reported in Table 1. Samples were manufactured at their MDD in layers of equal mass and volume using a volume-controlled rammer head and, immediately after compaction, they were removed from the mould and placed inside a curing room at 21±1 degrees

Table 1
Details of the mixes proposed in this study.

Mix number	Substrate	Cement (dry substrate wt%)	CCR (dry substrate wt%)	FA (dry substrate wt%)	OWC (dry substrate wt%)	MDD (MPT) (kg/m^3)
1	CL	10	–	–	9	1940
2	RCA	10	–	–	14	1980
3	RCA	5	–	5	14	1990
4	ELS	5	–	5	9	2100
5	ELS	–	6	25	14	2010
6	ELS	–	–	–	8	2160