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

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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 very 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.

KEYWORDS

stabilised rammed earth; life cycle assessment; consequential LCA; durability tests; mechanical strength; cumulative energy demand; waste materials; calcium carbide residue; fly ash; recycled concrete aggregate.

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

LIST OF 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

1. INTRODUCTION

Rammed earth (RE) is a very old construction technique that has recently experienced a revival in several parts of the 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 to centuries ago [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 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, if 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 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 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 soil mixes is given in Table 1. Extensive microstructural investigations of Mix 4, Mix 5 and Mix 6 were presented by the authors in [14, 15]. CL, RCA and ELS particle size distributions (PSDs) are presented in Figure 1.

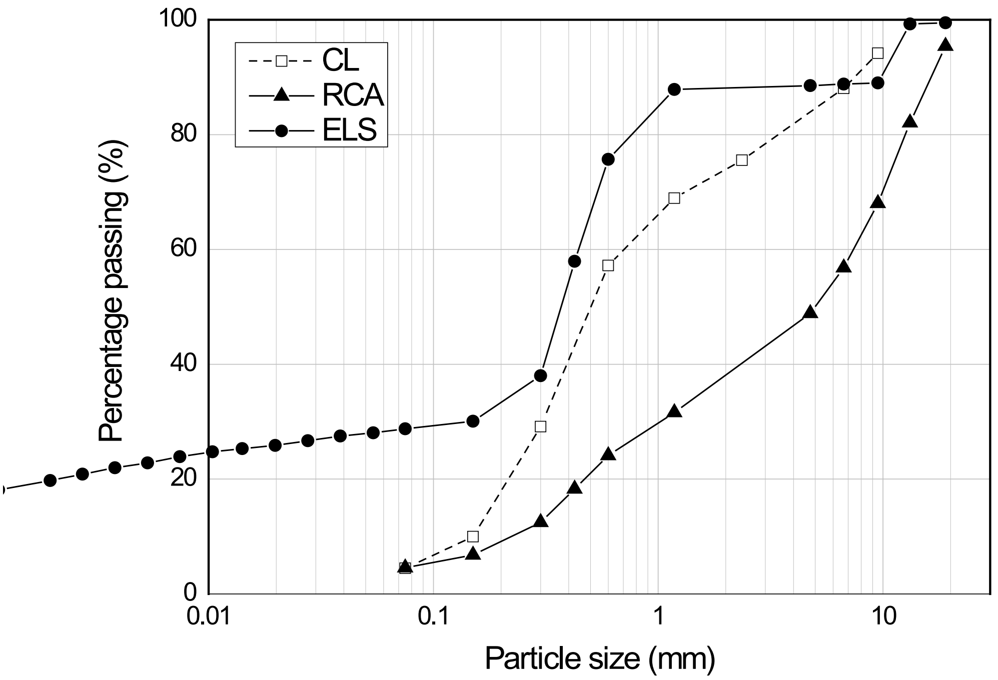

Figure 1: PSD for CL, RCA and ELS.

Table 1: Details of soil mixes proposed in this study.

Soil 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

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 Celsius and 96±2% relative humidity to prevent loss of moisture. A summary of the samples produced in this work is given in Table 2.

Table 2: Summary of tests and details of specimens used in the experimental program.

Test type	**Number of samples per soil mix**	**Dimensions of samples**	**Number of layers per sample**	**Mix 1**	**Mix 2**	**Mix 3**	**Mix 4**	**Mix 5**	**Mix 6**
UCS	4	ϕ100mm, 200mm high cylinder	5	yes	yes	yes	yes	yes	yes
AET	1	180mmx180mmx160mm prism	3	yes	no	yes	yes	yes	yes
WBT	4	ϕ100mm, 200mm high cylinder	5	no	yes	yes	yes	yes	no

3.1 Unconfined compressive strength

Unconfined Compressive Strength (UCS) is the primary means used by practitioners to compare the properties of RE materials. For this reason, the UCS is also often used as an indicator of a material's durability. UCS tests were performed following the methods proposed by Ciancio and Gibbings [18]. Specimens were tested at 28 days immediately after removal from the curing environment, preventing re-equilibration to atmospheric conditions. This step was taken to ensure suction similarity between specimens; although usually not considered a pertinent factor governing the strength of cement-stabilised RE, suction was demonstrated to be a key contributor to strength in unstabilised and lime-stabilised RE [19, 20]. Hence, suction equilibration was necessary to compare mix performance across stabilisers. Plywood sheets were placed between the specimen and the loading platens to uniformly spread the axial load and to avoid stress concentration effects on the specimen surfaces.

3.2 Accelerated Erosion Test

The Accelerated Erosion Test (AET) is recommended by HB 195 [21] to test durability of RE materials. In the test, a 150 mm diameter guarded section of the face of a prismatic specimen is sprayed with water for a period of one hour or until the jet of water spray completely penetrates the specimen. As the name evokes, the test attempts to simulate in a time frame of 1 hour the erosion damage a RE wall might experience during its lifespan. The jet of water was projected at 50 kPa, placed 470 mm from the sample. The maximum permissible erosion rate for all types of earth construction is one mm per minute, according to [21, 22]. Prisms were tested at 28 days, except for Mix 5: given the slower speed of lime-soil reactions, Mix 5 prism was left to cure for 56 days to provide sufficient strength. This test was carried out for all soil mixes except No. 2, for reasons discussed later in this paper.

3.3 Wire Brush Test

The Wire Brush Test (WBT), as presented in ASTM D559M [23], 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 height of the samples used in this work (200 mm) and the layers (5) differ from those proposed in ASTM D559M (116 mm and only one layer). These dimensions were chosen to permit UCS testing of specimens post-WBT [14]. The test is deemed successful if the weight loss is lower than 5%, according to Fitzmaurice [24]. The test was not performed on Mix 6 as unstabilised specimens slough material once submerged. Mix 1 was also not tested as numerous previous works have demonstrated its ability to pass the WBT (e.g. [25]). Given the slower speed of lime-soil reactions, Mix 5 specimens were left to cure for 28 days before commencing the wet and dry cycles instead of 7 days.

4. ENVIRONMENTAL IMPACT

One of the most complete methodologies to quantify the potential environmental impacts of a product or service is the Life Cycle Assessment, LCA [26]. ISO 14040 and ISO 14044 provide guidelines to perform an LCA study, and the present assessment was done according to these standards. The method is based on four major steps: i) goal and scope definition; ii) inventory analysis (LCI); iii) impact assessment; iv) interpretation of results.

4.1 Goal and scope

The goal of the present LCA study was to evaluate whether the impacts of the construction phase of an SRE building in WA could be reduced by varying the components of the mixture, in particular by means of employing waste materials. The building considered as case study was a typical CL SRE single family one story house with a footprint of 190 m^2, under construction at the time of the assessment.

4.2 Functional unit and system boundaries

The functional unit (FU) considered was the square meter of a 300 mm thick load-bearing RE wall. The life-cycle processes considered in the study were: i) raw material extraction; ii) production of mixtures' elements; and iii) transport of materials to the case study construction site. The boundary of the system studied is the construction site with a "cradle-to-gate" approach. The impacts considered independent from the choice of the mixtures' components were excluded from the study (e.g. energy expenditure for mixing the components and for erecting the wall). The cradle-to-gate assessment ceases when the building is occupied. A more complete "cradle-to-grave" assessment would include the building's operational phase (here, habitation) and destruction/decommissioning. An example consideration for the operational phase is the effect of mixture choice on the structure's thermal performance and so energy efficiency [27]. The end-of-life of the building material is something that should also be considered when assessing environmental performance. However, it is hard to predict end-of-life scenarios; even though the unstabilised mixture would certainly have some environmental advantage at the end-of-life due to its ease of re-use, there should not be major differences among the different end-of-life scenarios for the stabilised mixtures. Given the uncertainties post-construction, we focused on a cradle-to-gate approach.

4.3 Life cycle inventory modelling approach

Two modelling approaches exist for the LCI: *attributional* and *consequential*. The attributional approach *attributes* the inputs and outputs to the functional unit by linking the unit processes according to a specific normative rule [28]. The consequential approach seeks to capture the change in the environmental exchanges occurring as a *consequence* of adding or removing a specific human activity [29]. In our study, both the attributional and the consequential methodology were used to give a comprehensive understanding of the environmental impacts: the attributional approach was used to identify the hotspots of the system while the consequential approach was used to understand the consequences on the environment caused by a change in the choice of mixture's components.

In the attributional scenarios, the cut-off system model was applied and no credits were given to the producer of a valuable waste (such as a recyclable material). In the case of a unit process in the system with a joint co-production, an allocation key for the marketable co-products needed to be determined. The co-products should be marketable, otherwise they were considered as waste and available burden-free to the secondary user. The allocation key can be based on physical characteristics (such as mass or energy content) or on the revenue generated by the different co-products (economic or revenue allocation). Even though ISO 14044 encourages, when allocation cannot be avoided, partitioning of the inputs and outputs in a way that reflects the underlying physical relationships, physical allocation is considered to be unfair for users of co-products with low market values [30]. This was the case for the co-products used in our system, i.e. FA and CCR; the purpose of a coal power plant is to produce electricity and FA is just a by-product, while CCR is a nominally-useless co-product for the acetylene gas producer. No LCA study was found in literature considering the use of CCR, while the use of FA is fully explored from an LCA perspective. No unanimous approach has been applied in these studies though; while many authors partition the flows according to the prices of the electricity and the FA produced by the coal power plant (e.g. [31, 32]), many others consider FA a waste material and no flows are allocated to its production process (e.g. [33, 34]). In our opinion, the choice amongst the different allocation methods must be done according to the way FA is treated in the region under investigation: when FA is fully used, economic allocation should be considered; when part of the FA is disposed, FA should be considered as a waste. The problem of the allocation choice is solved in the consequential approach, where all the by-products are modelled as negative inputs instead of as positive outputs via a procedure called “system expansion” in the ISO standards. When the by-product is not a waste that needs a treatment (disposal or recycling), the material can substitute a *determining* product of a different production process. Credits from avoided emissions of this specific product are therefore allocated to the producer of the co-product.

In Australia about 44% of FA produced is effectively utilised in various value-added products, predominantly as a partial cement replacement in concrete elements, and the rest is disposed [35]. If we consider that in our mixture we used the part of the production that would be otherwise disposed, the material can be considered as a waste and no upstream impacts are associated with the material. In the consequential approach, the required information when using co-products is whether the market for the co-product is constrained. Since FA is partially disposed, it means that its market is unconstrained and an increase in the demand for FA can be provided without affecting other consumers. The FA is therefore available burden-free and the credits for the avoided landfilling should be accounted for as well. The same approach was used for RCA, obtained from construction and demolition (C&D) waste which is still landfilled for an important share. In 2011, more than 6 Mt of C&D waste (34% of the annual total) were landfilled in Australia. The percentage of landfilled C&D waste rises to 60% in WA, highlighting the environmental and economic benefits of partly recycling it [35].

The case of CCR is different: the by-product is considered a waste from the acetylene producer and it is landfilled or dumped indiscriminately in many countries around the world [36, 37]. In WA the acetylene producer pays a lime industry to take care of all the CCR produced. The lime industry, in turn, sells the unprocessed CCR to other industries that use the material to, for example, treat acid water from mining processes or to remediate acid sulphate soils. In an attributional approach, considering a revenue allocation, the point where the allocation is done would inevitably lead to different results: if the allocation is done at the gate of the acetylene plant, the CCR should be considered a waste without market value; if the allocation is done at the gate of the lime industry, an economic allocation could be done considering the new value of the CCR. This situation could in our opinion be modelled as a valuable waste that has a new market value after the treatment. With the cut-off approach, the only burden attributed to the secondary user should be the treatment process but, since no treatment is applied to the CCR, the product is available burden-free. The case is different when considering a consequential approach. The market for CCR is constrained: all the by-product is taken by the lime industry and sold. An additional demand for CCR will not increase the offer because the production volume is affected only by the market of its determining product: the acetylene gas. A change in the demand for CCR would therefore affect other activities that consume the product. These consumers will be forced out of the market and would look for an alternative product. The alternative product for CCR in the market would presumably be commercial hydrated lime. In a consequential approach, the use of CCR in the mixture will therefore have the same impact of using commercial hydrated lime.

4.4 Data quality

Due to the lack of publicly available specific data regarding emissions from production plants for materials used in this study, generic data from the Ecoinvent database were used [38]. The software SimaPro 8.2 was used for the LCA analysis implementation. As discussed previously, distances were modelled considering the example construction site located in the urban area of Perth, WA.

4.5 Impact assessment

The environmental categories considered in the assessment were the ones proposed by the European standard for the sustainability of construction works: abiotic resource depletion potential for elements (ADP elements); abiotic resource depletion potential of fossil fuels (ADP fossil fuels); global warming potential over 100 years (GWP); depletion potential of the stratospheric ozone layer (ODP); formation potential of tropospheric ozone photochemical oxidants (POCP); acidification potential of land and water (AP); eutrophication potential (EP) [39]. The characterisation factors for the impact assessment were taken from the baseline method developed by CML (Institute of Environmental Sciences of Leiden University, Netherlands) [40]. The Cumulative Energy Demand (CED) method, aimed to investigate both the direct energy uses and the indirect consumption of energy throughout the life-cycle of a good or service, was also applied to our case study [41]. Generic data adapted to the Australasian region were used to calculate the CED [42].

5. RESULTS

5.1 Unconfined Compressive Strength (UCS)

Stabilised mix strengths (1 to 5) were superior to the unstabilised mix (6) for all tested stabiliser combinations. Most significantly, all stabilised mixes exceeded the minimum dry (ambient) compressive strength requirement of 2.0 MPa according to HB 195, indicating all were suitable for RE construction. HB 195 provides no specification for unstabilised strengths but unstabilised mixes exceeded the 0.5 MPa design strength value recommended by NZS 4298. Nonetheless, if the present mixtures were intended to be used in real applications, specific requirements based on structural design should be considered.

Dry density is often cited as a metric to predict SRE strength: higher strengths are expected with higher dry densities (e.g. [43]). Although such relationships are true for unstabilised RE, comparing strength and dry density would not be appropriate here due to the use of differing stabiliser types. Rather, mix performance was strongly affected by stabiliser content and substrate. For equal amounts of cement, Mix 1 (crushed limestone) achieved almost double the strength of Mix 2 (RCA). Replacing half the cement content with FA between mixes 2 and 3 (whilst maintaining similar compacted density and water contents) reduced mean strength by 23%. Overall, mixes comprising combinations of alternative stabilisers (Mixes 3, 4 and 5) performed more poorly than those using cement (Mixes 1 and 2). UCS results, dry densities and water contents at testing are reported in Figure 2. Although density and water content probably affected the compressive resistance results, Figure 2 shows that they are not good indicators to predict the strength of stabilised mixtures.

It is noted that all mix UCSs were assessed at 28 days in consonance with concrete testing, which may not have been sufficient curing time to mobilise the full strength (or a closer approximation to it) of lime-stabilised specimens. Mix 5 UCS is therefore expected to improve with longer curing time. Performance may also improve with different ratios of CCR and FA. Determining optimal proportions or curing times was outside the scope of this work but is a topic of ongoing study.

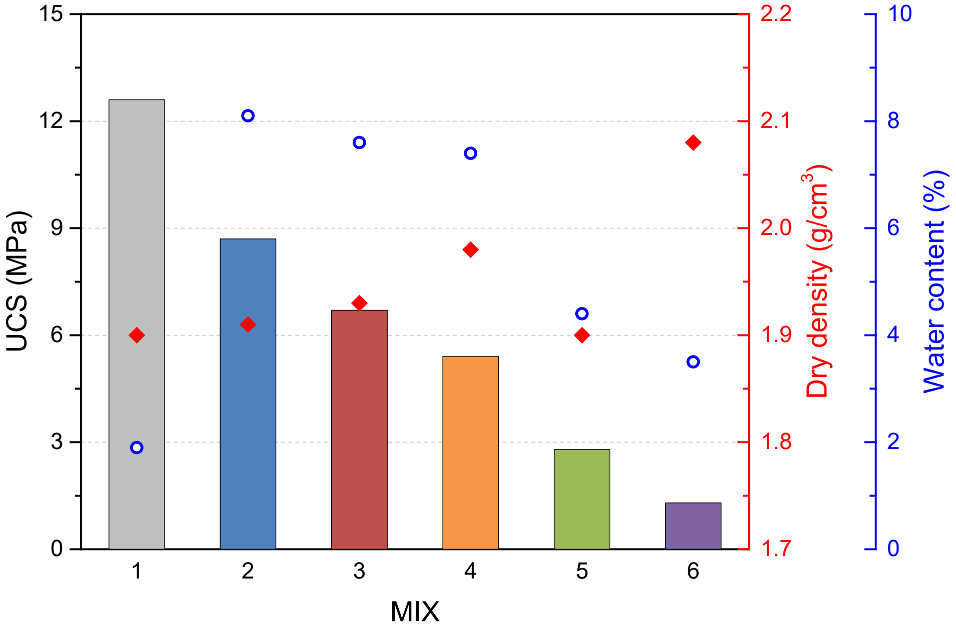

Figure 2: 28-day Unconfined Compressive Strength results for the different mixes. Red rhombuses indicate the average dry densities at testing (second y-axis) while blue circles indicate the average water contents at testing (third y-axis).

5.2 *Accelerated Erosion and Wire Brush testing*

Figure 3 shows Mix 3, 4, 5 and 6 specimen faces at the end of the AET. Mixes 1, 3 (Figure 3a) and 5 (Figure 3c) did not show any visible erosion after 60 minutes, demonstrating excellent durability properties. Mix 2 was not tested as Mix 3 (Figure 3a), with half the cement content, easily passed the AET. Mix 4 (Figure 3b) had some minimal localised erosion but amply passed the test. Mix 6 (Figure 3d), however, did not pass: after 30 minutes the specimen was completely penetrated. Even though the test represented conditions far more severe than occur in reality, it is undeniable that a mixture without any stabiliser must be protected from the rain to avoid erosion (and consequently excessive maintenance). Protection could be in the form of waterproofing agents, sloping roofs and large eaves. Cement-stabilised specimens passed the AET with ease: even with a minimal amount of stabiliser (5 wt%) the erosion was null or minimal. However, it was noteworthy that all stabilised specimens, regardless of stabiliser type, passed the AET.

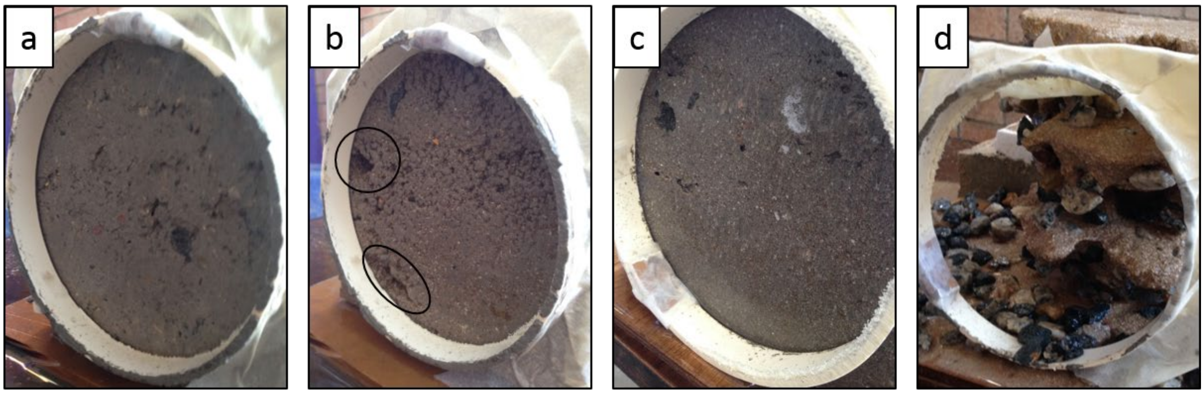

Figure 3: state of the samples after the AET. a), b) and c) show the state of the sample of Mix 3, 4 and 5 respectively after 60 min. d) shows the complete erosion of the sample from Mix 6 after 30 minutes.

No volume change was measured during WBT; measurements to the nearest 0.2mm were perhaps too coarse to detect volume changes for the mixes used. Mass losses were highly affected by compaction quality: poor quality specimens suffered damage around the uppermost compacted layer on submersion (Figure 4a and b). All specimens suffered mass loss due to submersion to some level, however losses were minimal for well-compacted specimens (e.g. Figure 4c and d). From Figure 4 it is clear how the quality of the manufacturing could lead to opposite results in terms of mass loss. Notably, however, even the specimen represented in Figure 4a and b had brushing mass losses lower than the 5% limit set by Fitzmaurice. Nevertheless, total losses (i.e. including submersion) reached 9.6%. The specimen represented in Figure 4c and d, instead, had a mass loss due to brushing equal to 0.9%, and negligible losses when submerged. Figure 4d highlights the negligible losses at the end of the test for the well compacted specimen. Excepting poor specimens, all stabilised mixes exceeded the minimum requirements. Mass lost due solely to brushing and total mass losses are given in Table 3. Brushing losses were measured by weighing specimens before and after brushing per cycle. Total mass losses, which included brushing and submersion losses, were calculated according to the formulas presented in ASTM D559M assuming average values (given in the Standard) for the amount of water reacting with the stabiliser during testing. Note that this assumption may not have reflected the maturity or chemistry of different stabiliser reactions; determining more appropriate values was not part of this work but is a topic that could be investigated further. Using this approach, total mass losses for mixes containing RCA (Mixes 2 and 3) were *negative*, i.e. mass was seemingly gained during the test, suggesting that the average value for the retained water for soils belonging to the A1 AASHTO category was too low for RCA. Such a result may be due to residual mortar surrounding the RCA aggregates modifying the imbibition properties with respect to the inert aggregate [44]; further investigations into the effect of RCA content on mass loss calculations were outside the scope of this work. Negative mass losses were not reported in Table 3. Results for mixes containing ELS (Mixes 4 and 5), belonging to the A2 AASHTO category, were more realistic and demonstrated how the majority of the losses were due to the long exposure to water.

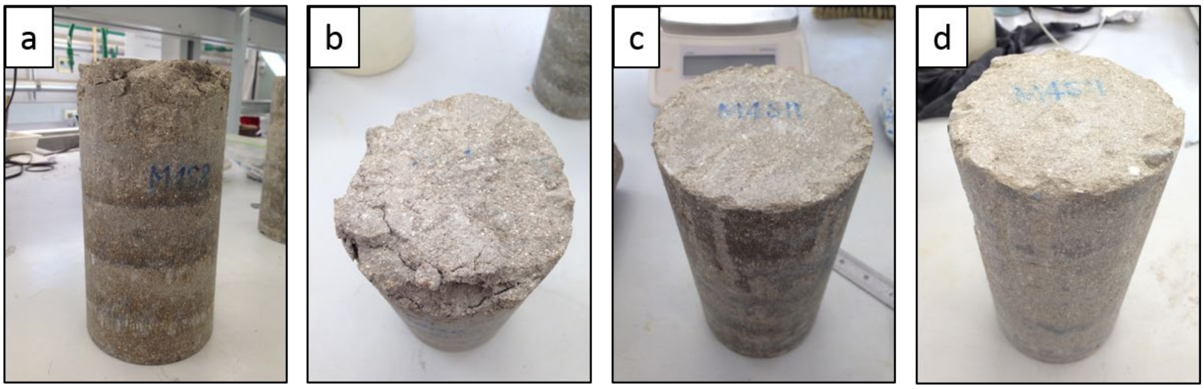

Figure 4: difference in WBT results according to the manufacturing quality of the specimen. a) and b) show the condition of a specimen from Mix 5 that was not well compacted after the first submersion. c) and d) show a specimen made from the same mixture but well compacted, after the first submersion and at the end of the test.

Table 3: WBT results for all the mixes tested. Mass losses indicate the percentage of mass losses due to the wire-brushing for the well compacted specimens. *The calculation may not be reliable because the assumptions in the D559M formulas may not have reflected the chemistry of the different stabilisation methods.

Mix	**Mass losses (brushing)** [wt%]	**Mass losses D559M** [wt%]	**Pass/fail**
2	0.1	-	Pass
3	1.5	-	Pass
4	0.6	5.4*	Pass
5	0.9	3.0	Pass

5.3 Environmental impact results

5.3.1 Attributional LCA

A comparison of the LCA results studied with an attributional approach is presented in Figure 5. Results show that all mixes performed better than Mix 1, used in the case study, for all the environmental impact categories considered.

Choice of stabiliser affected overall environmental impact far more significantly than choice of inert fraction. Mixes incorporating cement had the highest environmental impact. For the base case, emissions and resource depletion connected to the clinker production process were the main contributors to poorer performance. Contrasting Mixes 3 and 4, RCA achieved a lower environmental impact than ELS in all categories. RCA was available burden-free and, in this case, shorter distances were needed to transport material from the demolition site to the new construction site as compared to transporting materials from a quarry outside the city. Varying ELS components would affect this balance, however, for example reducing the clay content to reduce transportation when chemical binders are already added to the mixture. Equally, sourcing CL from a close quarry improved Mix 1 performance in all categories except eutrophication and acidification, which arise from the high nitrogen oxide emissions during the limestone blasting process.

Contrasting Mixes 4 and 5, the use of alternative stabilisers reduced environmental impact by between 50 and 100% per category. Overall, eliminating cement reduced environmental impact by up to 85% compared to the base case. Notably, ELS stabilised using waste material and ELS unstabilised (Mixes 5 and 6 respectively) had similar impacts (i.e. similar reductions with respect to cement-stabilised mixes) as transported components were needed to manufacture the base ELS mix.

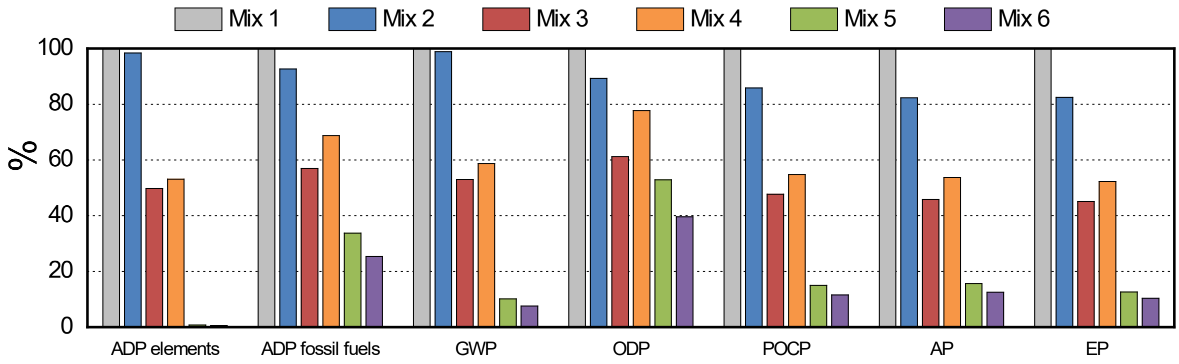

Figure 5: Life Cycle Assessment results for the 7 environmental categories required by the EN 15978 calculated with the CML Baseline Method with an attributional approach. % is normalized to the base case (Mix 1).

5.3.2 Consequential LCA

Figure 6 compares mix performance from a consequential perspective. Relative results between the mixes were similar to the attributional approach except for Mix 5, which contained CCR. If we assumed that the market for CCR was constrained (i.e. the product was fully utilised) and that an input to the system of CCR was equivalent to an input of commercial hydrated lime, impacts of Mix 5 were *higher* than the base case (mix 1) for some impact categories due to higher Halon 1301 and carbon monoxide emissions. Indeed, Mix 5 results were worse than those mixes stabilised with a small fraction of cement (i.e. Mixes 3 and 4) in most of the environmental categories. Abiotic depletion and eutrophication were an exception because of the environmental benefits of re-using a higher amount of a waste material (i.e. FA) that would otherwise be landfilled. Opposite results were obtained if we considered CCR to not be fully utilised, as happens in many countries. In this case, results would be extremely positive for Mix 5. A method to exploit this in Perth would be to obtain CCR from other regions or countries where it is still disposed. Although the transportation cost and impact would increase, considering transport by boat, Mix 5 would still outperform the base case even if CCR was sourced from the other side of the world.

It should be noted that the consequential approach used here was extremely penalising and assumed that hydrated lime and CCR were substitutable. Such an assumption may not be valid as CCR is used for few applications where price of the lime is the priority rather than quality or form of the chemical admixture. Hence, an increase of the material value could lead to a completely different market situation, where the CCR producer would not pay to get rid of its by-product but would simply put the material on the market. In that case, an economic allocation could be implemented to assess the environmental impacts or, in a consequential approach, CCR could substitute hydrated lime.

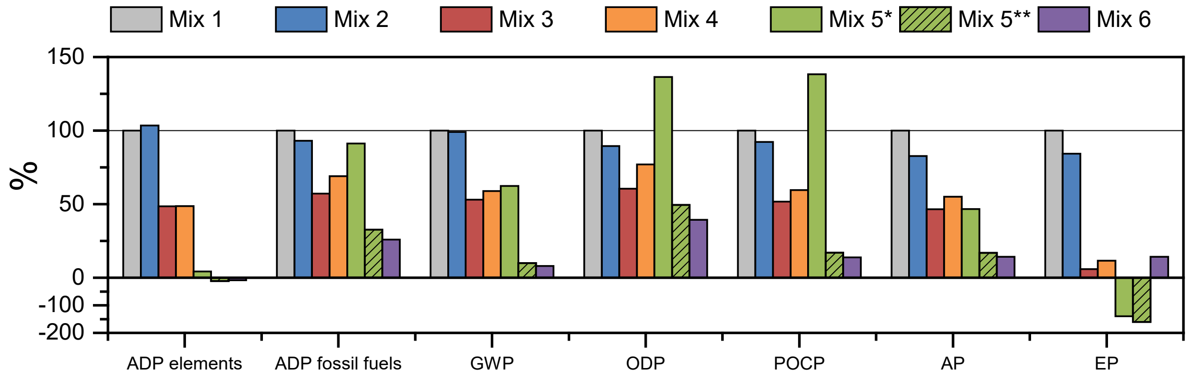

Figure 6: Life Cycle Assessment results for the 7 environmental categories required by the EN 15978 calculated with the CML Baseline Method with a consequential approach. % is normalised to the base case (Mix 1). *Mix 5 in case CCR is a fully-utilised by-product. ** Mix 5 in case CCR is not a fully-utilised by-product

5.3.3 Cumulative Energy Demand

Cumulative energy demand (CED) provides a value for total energy use throughout a given life-cycle. CED results per mix, reported in Figure 7, were obtained using an attributional approach and data from the Australasian LCI database and demonstrated that almost 100% of the energy demand for each mix came from fossil fuels, mainly oil and coal. Fossil fuel use represented energy required for sintering the clinker and for fuelling the vehicles to transport the materials. Hence, mixes incorporating cement had the greatest impact; for example, halving the amount of cement between Mixes 2 and 3 saved 103 MJ per m^2 of wall, while using clay as the only binder (Mix 6) saved up to 174 MJ.

Notably, CED results were heavily influenced by the low renewable component of the Australian energy mix; a greater renewable component would reduce the fossil fuel energy demand. As found previously, Mix 3 outperformed Mix 4 due to reduced transportation of RCA with respect to ELS. Using only alternative stabilisers (i.e. Mix 5) reduced the energy demand by eliminating cement but CED remained roughly 30% of the base case due to transportation.

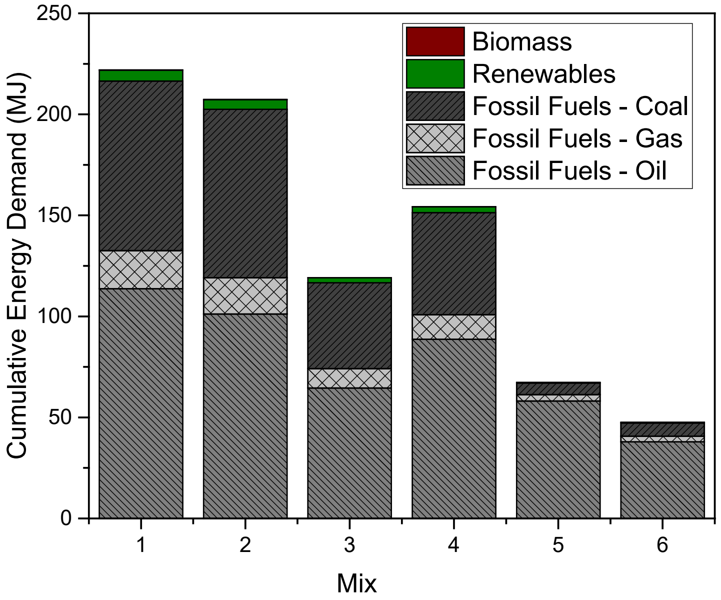

Figure 7: CED results for the different RE mixes. Results are subdivided for the different energy sources using an attributional approach and data from the Australasian LCI database.

6. DISCUSSION

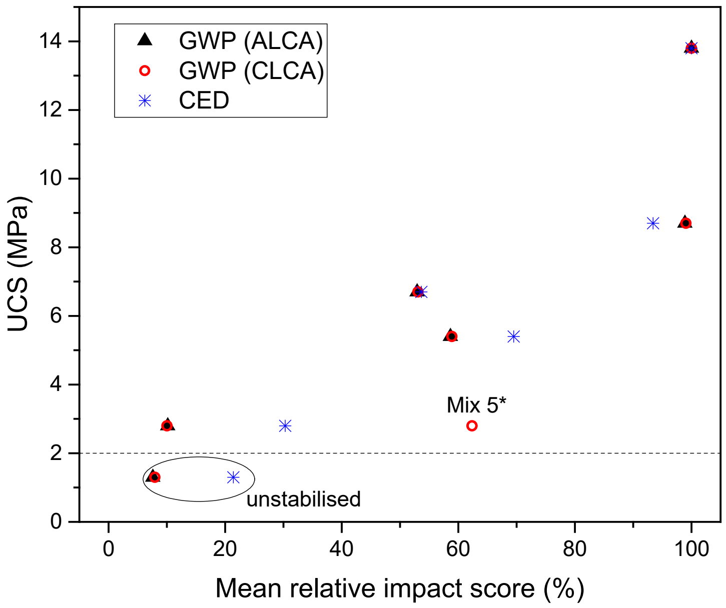

Figure 8: UCS vs mean relative impact score (GWP (ALCA), GWP (CLCA) and CED relative to mix 1) for all tested soil mixes. Mix 5* represents the case CCR is a fully utilised by-product.

Outcomes of the experimental campaign gave us some indications on the relevance of the durability testing techniques investigated. AET proved to be a good indicator of the erosion resistance of cement-free specimens. However, the AET simply wasted water for stabilised specimens and could not differentiate between them. On the other hand, WBT was a good indicator of the durability of the material when exposed to extreme weather conditions but it could not be performed on unstabilised specimens. Furthermore, formulas attuned to the different stabilisation methods, e.g. cement or CCR, are required to appropriately determine the mass losses at the end of the test. UCS was not a good indicator of the durability of the specimens: all the stabilised specimens passed the durability tests even though they were characterised by very different compressive strengths. Increasing test severity could perhaps differentiate between materials but would detract from the potential real-world relevance (i.e. no longer representative of weather erosion).

Durability was assessed in the present work in terms of alterations induced by water. Although erosion is the major cause of concern when dealing with earthen structures, additional durability issues may arise when stabilisers and different substrates are used. Alkali-aggregate reactions and sulphate induced swelling are typical examples of durability concern when mortar-like systems are considered. While assessing these properties was beyond the scope of the present paper, further investigations needs to be performed if, for example, RCA was intended to be used as a substrate instead of earth for SRE applications.

Even though all but the unstabilised mix (Mix 6) passed the WBT and AET tests and achieved sufficient strengths for construction according to HB 195, environmental impact, judged by attributional and consequential LCA and CED assessments, varied considerably. A comparison of relative environmental impact in terms of GWP against UCS is shown in Figure 8. Among the environmental impact indicators, GWP was decided to be shown due to the public concern and the relevance of the relative environmental category (i.e. climate change). Nonetheless, results for the environmental indicators not-shown in the figure exhibit similar trends to GWP. For those mixes tested, environmental impact (relative to that of Mix 1) increased almost monotonically with UCS despite the various contributing factors to each mix's impact (e.g. varying significance of transportation, sintering etc.). In other words, specifying higher UCS, as might be done to secure a higher perceived durability, proportionally increased the environmental impact of the mix.

As previously discussed, mix environmental performance was heavily influenced by cement manufacture and transportation. Hence, SRE performance could be improved by reducing cement content, using alternative binders and reducing transportation of the substrate. The environmental benefits of using 'waste' soil depended most significantly on its grading suitability and the proximity of quarries needed for any additional material. The use of waste materials as binding agents is highly recommended in terms of environmental impacts. However, as for the case of Mix 5, the benefits of using CCR could be offset if it were a fully utilised by-product, rather than waste, and it was substituted directly for commercial hydrated lime. Notably, eliminating stabilisers neither nullified the environmental impact, as transportation was still required (for our case), nor provided sufficient strength or durability for construction.

The use of generic data from the Ecoinvent database and global characterisation factors in the LCA analyses may have reduced the accuracy of the results. The development of regional-based characterisation factors and datasets, transparent on the allocation procedures adopted and comprising the full range of emissions, would be therefore desirable to increase the quality the study. Nevertheless, the environmental ranking of the mixes presented would not be revolutionised by the use of more accurate data. On the other hand, a more accurate discussion of the local environmental impacts could have been presented if detailed characterisation factors were available. Moreover, the LCA analysis could be further improved if the effect of the mixture's selection on the energetic consumptions of the building and the end-of-life were taken into account. Nevertheless, additional hygrothermal experiments, reliable models integrating physical processes into a code of hygrothermal calculations and primary end-of-life data at the moment unavailable would be necessary for such a study. Finally, a life-cycle costing analysis of the different mixtures would be of primary interest for RE practitioners. Although the analysis could not be performed due to missing information, it is reasonable to believe that using untreated waste materials would be cheaper than employing traditional packed stabilisers. On the other hand, the most economical solution would probably remain the use soil available on-site.

7. CONCLUSIONS

This paper addressed the issue of the environmental impact of specifying excessive SRE mix strengths to provide sufficient durability. For those mixes tested, our experiments demonstrated that UCS was not a good indicator of durability; all stabilised mixes passed the minimum strength requirement of HB 195, the AET and WBT tests. Durability results were highly dependent on compaction quality, indicating the need for good quality control when performing these tests.

Mixes comprising cement boasted the highest UCS but also the worst environmental impacts of all tested mixes. Reducing cement content resulted in a considerable energy saving. Replacing cement with CCR and FA improved environmental performance but, in a consequential approach, overall impact was significantly affected by whether CCR was a waste, a fully-utilised by-product or a marketed good directly substitutable for commercial hydrated lime.

Although using unstabilised mixes might be considered environmentally friendly, we found that the environmental impacts of unstabilised material and those stabilised with waste products were similar when soil available on site was not suitable by itself for construction. Furthermore, unstabilised material failed all strength and durability criteria. Hence, the use of waste materials is highly recommended to reduce landfilling and to reduce the abiotic depletion as well as all the environmental impacts related to the production of energy intensive binders.

ACKNOWLEDGMENTS

The authors would like to thank Claudio Marcon and Daniele Rossi for their contribution in the design of the graphical abstract.

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