



# Weathering's beneficial effect on waste-stabilised rammed earth: a chemical and microstructural investigation



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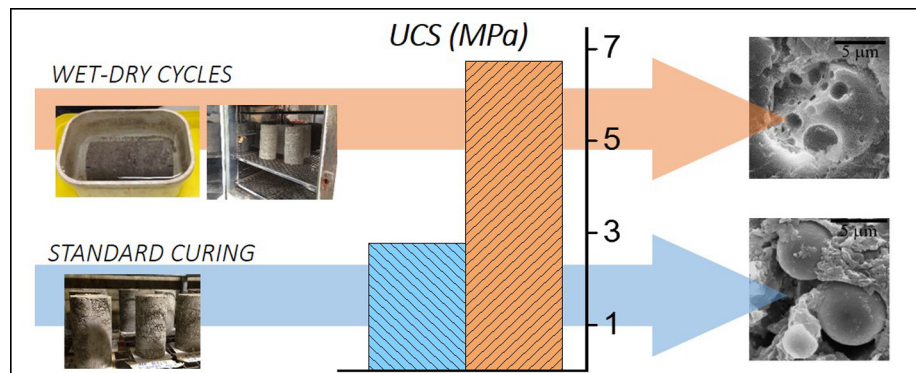
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## HIGHLIGHTS

- Microstructure of RE stabilised with waste materials has been investigated.
- Weathering improved the mechanical strength of SRE mixes.
- Fly ash promoted autogenous healing during wet-dry cycles.
- Waste materials proved to be an effective solution to stabilise non-expansive soils.

## GRAPHICAL ABSTRACT



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## ABSTRACT

The most common method to improve the mechanical properties of a rammed earth mix is to add chemical stabilisers like cement and/or lime. Varying the stabiliser type will affect strength gain but also the environmental impact. In this paper, the effect of wetting-drying cycles on the long-term unconfined compressive strength of stabilised rammed earth (SRE) mixes was investigated through the chemical characterisation of the soil components and microstructural analyses. The mixes were stabilised using different agents characterised by distinct environmental impacts, such as cement, calcium carbide residue and fly ash. These last two are considered waste materials, significantly affecting their use's associated environmental implications. The results of this experimental campaign support others in this series of work and showed an improvement of the mechanical properties after cyclic wetting-drying due to the formation of new hydration products which bound particles together. The use of waste materials proved to be an effective solution to stabilise RE.

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## 1. Introduction

Rammed earth (RE) is an ancient building technique that consists of compacting slightly wet soil in layers within formwork. The high density due to compaction and the suction of the partially saturated micro-pores give RE materials a compressive strength of 0.5–2.5 MPa [1]. In order to meet modern construction standards

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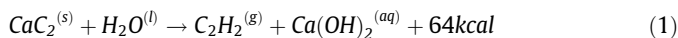
and requirements, stabilisers are added to RE mixtures in many countries around the world [2–4]. The most used stabilisers are cement and lime but the need to reduce the environmental impacts in the building sector demands the use of more sustainable stabilisers (e.g. waste materials, biopolymers and geopolymers [5–13]).

One of the waste materials traditionally used for soil stabilisation is Fly Ash (FA), the fine particle residue transported by flue gas as a result of power generation from coal-fired power stations. FA chemical composition depends on the coal ignited and typically comprises aluminosilicates with some iron and/or calcium oxides and minor concentrations of Na, Mg, P, S, K, Ti, Sr and Ba. Typically, FA has quartz and mullite as major crystalline phases and 40–80% by weight (wt%) of amorphous phases. FA represents 85–95 wt% of the total ash generated from coal combustion, which accounts for 5–20 wt% of feed coal [14]. Coal is and will remain until 2030 the second-largest energy source worldwide, with an average increase rate of 0.6%/year [15]. An estimate of annual worldwide generation of FA is approximately 780 million tonnes [16]. Even though efforts have been undertaken to recycle some FA, the remainder is waste and has to be discharged into ash ponds, lagoons or landfills. The main uses for recycling FA are concrete production, road base construction, soil amendment, zeolite synthesis and use as a filler in polymers. The effect of FA on the compressive strength of soil is due not only to its free lime content alone but also to hydraulic and pozzolanic reactions [17]. FA rich in free lime is self-cementing while FA containing a low amount of lime needs an activator such as Portland cement or added lime to produce cementitious compounds [18].

Soil stabilisation is a well-established discipline within geotechnical engineering. Cement is preferred for lowly cohesive (sandy) soils but it loses effectiveness for highly plastic soils. For sandy soils, RE literature recommends a cement content in the range of 5–12% of soil mass, considering that the compressive strength of the mixture nominally increases linearly with the increase in cement content [19]. Cement is the most commonly used stabiliser and its popularity is due to quick strength gain and the ability to obtain desirable mechanical properties with relatively low amounts of stabiliser. Portland cement mixed with water gives rise to hydrated compounds, such as calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH), which cover the soil particles and later crystallise to link them [18].

Lime stabilisation is the preferred methods for plastic clays. The addition of lime results in an immediate cation exchange, in which calcium ions normally replace cations on the clay surface. The high alkaline pH resulting from lime treatment leads to long term pozzolanic reactions: silica and alumina dissolved from the clay mineral structure react with  $\text{Ca}^{2+}$  in the pore water to form CSH and CAH in a similar process to cement hydration [20]. The formation of cementing agents is considered the main source of strength improvements in lime stabilised soils and it is strongly dependant on the structure of the soil, the temperature and the soil water content [21,22]. Finally, carbonation is a reaction between lime and carbon dioxide present in the air to form calcium carbonate. For soil stabilisation carbonation should be avoided as calcium carbonate is a less effective stabiliser than hydration products [23,24].

Two different types of lime are available to stabilise soils: *hydraulic* and *hydrated* lime. Differences derive from the chemical composition of the original limestone and while the hydraulic lime sets through hydration (with a similar behaviour to cement), hydrated lime sets through carbonation and needs a pozzolanic material to form cementitious products. A by-product that has very similar chemical and mineralogical composition of hydrated lime is carbide lime, also known under the name “Calcium Carbide Residue” (CCR) [25]. CCR is a by-product of acetylene production through the hydrolysis of calcium carbide



CCR has been already used for agricultural purposes, water treatment, soil stabilisation, mortars and compressed blocks. The first attempts to use CCR as a stabiliser for masonry units were presented by Horpibulsuk et al. [26] and by Consoli et al. [27], while the feasibility and the environmental advantages of using CCR combined with FA for RE construction were presented in [28]. Using CCR as substitute for commercial hydrated lime would reduce the concerns related to its waste disposal and all the environmental impacts related to limestone exploitation and calcination.

Most of the studies on RE stabilisation focus on the mechanical properties of the material on a short-term basis (e.g. 28-day strengths), while long term performance is often ignored. However, weathering cycles over the material's lifespan may effect mechanical performance. In this study, we investigated the strengths of stabilised rammed earth (SRE) materials, stabilised with either cement or waste materials (i.e. CCR and FA) before and after wetting–drying regimes. Particular emphasis was given to the long-term behaviour of the alternative stabilisation by relating the mechanical properties and durability to material microstructural features.

## 2. Materials and methods

### 2.1. Materials

#### 2.1.1. Engineered soil

Although several studies on earthen construction indicate that the Particle Size distribution (PSD) cannot be used as a discriminating parameter for the selection of a suitable soil for construction [29,30], a heterogeneous PSD, including both fine and coarse particles, is generally recommended when building with earth [31,32]. Moreover, laboratory tests tend to underline that the activity of the clayey proportion in the soil is at least as impacting as its PSD [33]. The base *in situ* soil used here was a typical soil from Perth, Western Australia, which largely comprised sand. To improve its poor grading, both coarse (gravel) and fine particles (silty clay) from local quarries were added. The percentage of the single components were determined following the recommendations made by Houben and Guillaud [32]. The use of an “engineered” soil over a natural soil permitted tighter control over material mineralogy and grading [23]. The resulting mixture, which will be referred to as Engineered Local Soil (ELS), was composed of 60% local soil, 30% clayey soil from a nearby quarry and 10% single sized gravel (10 mm). The PSD of the added silty clay, measured according to AS 1289.3.6.1 [34] and AS 1289.3.6.3 [35], demonstrated a composition of 66% clay and 28% silt. Chemical analysis showed a composition of 65% kaolin, 28% quartz and 5% muscovite. X-ray diffraction analysis on an oriented and glycolated sample of the silty clay revealed no presence of expansive clays and confirmed the typical low-activity of the kaolinite. The specific gravity of the silty clay soil, calculated according to AS 1289.3.5.1 [36], was 2.75 g/cm<sup>3</sup>. The PSD of the ELS is shown in Fig. 1.

#### 2.1.2. Stabilisers

The cement (CEM) used is a General Purpose Cement Type GP according to AS 3972 [37] composed of Portland cement and limestone (less than 7%). FA came from a coal power plant in Western Australia (WA) and had a median particle diameter of 15 μm. Chemical compositions of CEM and FA are reported in Table 1 and PSDs are shown in Fig. 1. The FA composition showed a low calcium content and was therefore classified as class F ash based on ASTM Standard Specification C 618 [38]. CCR was provided by an acetylene producer located in WA and comprised calcium

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