Rammed Earth stabilised with waste materials: a sustainable and resistant solution

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Rammed Earth stabilised with waste materials: a sustainable and resistant solution

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Abstract. Earthen dwellings are part of the vernacular architecture and cultural heritage of many countries in the Mediterranean region, and a renovated interest towards these types of structures is now widespread in the same countries mainly due to sustainability reasons. However, poor resistance to weathering compromises their durability and their popular acceptance. A fascinating option to improve the resistance of earthen structures while preserving their environmental sustainability is to use locally available waste materials as stabilisers. In this paper, the evolution over time of the mechanical resistance of rammed earth stabilised with residues from widespread industrial processes (i.e. fly ash from coal combustion and calcium carbide residue from acetylene production) was investigated. Waste-stabilisation prompted optimal long-term mechanical resistance; on the other hand, laboratory samples exhibited low compressive strengths in the short-term when cured under standard conditions. The addition of a supplementary industrial residue (i.e. gypsum from flue gas desulfurization) was explored to enhance the early-age strength. Results confirmed the short-term strength benefits induced by gypsum addition.

1. Introduction

Earthen dwellings are part of the vernacular architecture and cultural heritage of the Mediterranean regions: Northern Africa, Southern Europe and Levantine coast [1][2]. A renovated interest towards these types of structures, such as rammed earth, is now widespread in many countries around the world, including the Mediterranean ones, due mainly to sustainability reasons [3]. However, poor resistance to weathering compromises earthen structures durability and their popular acceptance [4]. Stabilisation undeniably improves the mechanical strength of earthen buildings and its resistance to erosion, swell and shrinkage [5]. Nevertheless, the greenhouse gas emissions associated to the production of traditional stabilisers (i.e. cement and lime) are a non-negligible side effect of stabilisation [6]. A fascinating option to improve the resistance of the earthen mixture while preserving its environmental sustainability is to use locally available waste materials as stabilisers. In a previous

study, the evolution over time of the mechanical resistance of rammed earth stabilised with residues from widespread industrial processes, such as coal power and acetylene productions, was investigated [7]. Waste-stabilisation prompted optimal long-term mechanical resistance; on the other hand, laboratory samples exhibited low compressive strengths in the short-term when cured under standard conditions. In the present study, the addition of a supplementary industrial residue (i.e. gypsum from flue gas desulfurization) was here explored to enhance the early-age strength of the earthen mixtures under investigation. The underlying assumption was that gypsum could accelerate the typically slow pozzolanic reactions developing between soil and stabilisers, which generate hydration products that increase the strength of the material [8]. In fact, (phospho)gypsum has already been successfully used to improve the mechanical properties of lime-fly ash blends for brick applications [9][10]. The goal of the present study was therefore to understand whether the addition of waste gypsum could improve the short-term mechanical resistance of earthen structures. To do so, the short and long-term unconfined compressive strength of waste-stabilised rammed earth with and without the addition of gypsum from flue gas desulfurization were compared. Finally, to explain the different behaviour, microstructural analyses of the crushed specimens were also performed.

2. Materials

2.1. Substrate

Substrate for the stabilised rammed earth mixture was provided by Minerali Industriali S.r.l. [11], which sourced the raw material from a quarry in the Northern part of Italy. Particle size distribution of the earthen substrate was obtained via sieving and sedimentation following the ISO 17892 -4:2016 standard [12]. The earth showed a composition of 36% clay, 44% silt and 20% sand (Figure 1). On the other hand, the elemental composition, assessed via X-ray fluorescence, is presented in Table 1 in terms of oxides weight percentage and highlighted a large presence of silica, alumina and iron oxides. X-ray diffraction confirmed the predominance of quartz in the earth and the presence of two clay fractions: vermiculite and illite. Loss on ignition (LOI) highlighted the presence of carbon, likely organic carbon, in addition to a minor amount of carbonates.

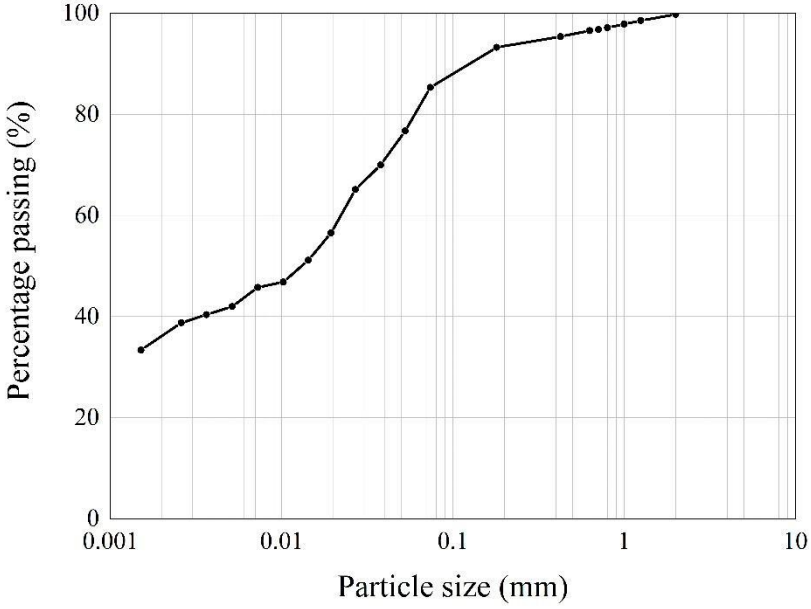

Figure 1. Particle size distribution of the earthen substrate.

Table 1. X-ray fluorescence elemental composition of the earthen substrate, fly ash (FA) and flue gas desulfurization gypsum (FGDG) in terms of main oxides weight percentage (LOI: Loss On Ignition).

	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	K_2O	Na_2O	CO_2	SO_3	P_2O_5	LOI
Substrate	64.1	18.0	6.0	1.0	0.7	0.8	1.6	0.5	0.9	0.1	0.0	6.9
FA	38.5	39.8	6.7	1.4	7.7	0.0	0.6	0.0	0.0	0.5	4.4	-
FGDG	3.2	1.2	4.6	1.4	36.3	0.9	0.1	0.2	0.0	37.0	0.0	15.1

2.2. Additives

Three different by-products of industrial processes were used as additives to the earthen substrate: calcium carbide residue (CCR), fly ash (FA) and flue gas desulfurization gypsum (FGDG). CCR was sourced from an acetylene plant in the hinterland of Milan. The material was in an aqueous slurry form and the solid fraction (approximately 30 wt.%) resulted to be, according to X-ray diffraction analysis, portlandite for the vast majority, i.e. $Ca(OH)_2$, with traces of calcite ($CaCO_3$). FA was provided by an Italian thermal power plant and the chemical composition was analysed via X-ray fluorescence (table 1). Light elements were not detected by the instrument, while heavy elements were found in low amounts; as expected, the LOI was negligible. The low calcium content classified the material as class F based on ASTM Standard C618 [13]. X-ray fluorescence analysis results of FGDG, sourced from an Italian thermal power plant too, are reported in the same table and identified as main components of the material sulphur and calcium. Sulphur oxide amount was estimated by difference and the result is consistent with the LOI, which was mainly due to gypsum crystallization water.

3. Methods

3.1. Specimens manufacture

Composition of the base mixture (i.e. earthen substrate mixed with 6% CCR and 25% FA on a dry weight basis) was the result of a prior research from which the present study developed [7]. A small amount of FGDG (i.e. 1% on a dry weight basis) was then added to the base mixture to see the effect on the short and long-term compressive strength. 38-mm wide and 76-mm high cylinders were prepared to assess the Unconfined Compressive Strength (UCS). Since the substrate lacked coarse particles, the representativeness of the material could be guaranteed with specimens of small dimensions. Specimens were manufactured at their optimum dry density obtained via modified proctor test [14]. Once the materials were heterogeneously mixed, the mixture was compacted in a mould using a mechanical press. Thereafter, specimens were left to cure in boxes at constant high humidity (approx. 97%, obtained via saturated K_2SO_4 salt solution) and temperature (approx. 22°C). Specimens were then tested for mechanical resistance at 3 different curing times: 7, 28 and 56 days. For each mix and curing condition, at least 3 specimens were manufactured.

3.2. Mechanical resistance

UCS of the specimens was tested with a triaxial load frame TRITECH at constant displacement rate of 0.3 mm/min until failure. Specimens were oven-dried immediately after testing to determine their dry density and water content.

3.3. Microstructural characterization

Samples from compressed specimens were analysed via thermogravimetry and scanning electron microscopy (SEM) to investigate the microstructural evolution. A Seiko 6300 and a Cambridge Stereoscan 360 were used for the different analyses, respectively.

4. Results

4.1. Mechanical resistance

Optimum water content for the base mixture (i.e. without FGDG) resulted to be approximately 21.5%, corresponding to a maximum dry density of 1.62 g/cm^3. The same weight per unit volume was the target density for specimens containing 1% of FGDG too, in order to minimize the effect of variations in the dry density on the compressive strength results. UCS results for specimens with and without FGDG are reported in figure 2 together with their dry densities at testing. Error bars in the figure represent the minimum and maximum compressive strengths obtained for each group of specimens. In the figure, the 2 MPa line was highlighted since it is considered by several standards, such as the Australian one [15], the minimum acceptable resistance to build with earth. Results showed that the mixture containing FGDG was stronger at each testing time and, differently from the mixture without FGDG, reached a compressive strength higher than 2 MPa at 28 days.

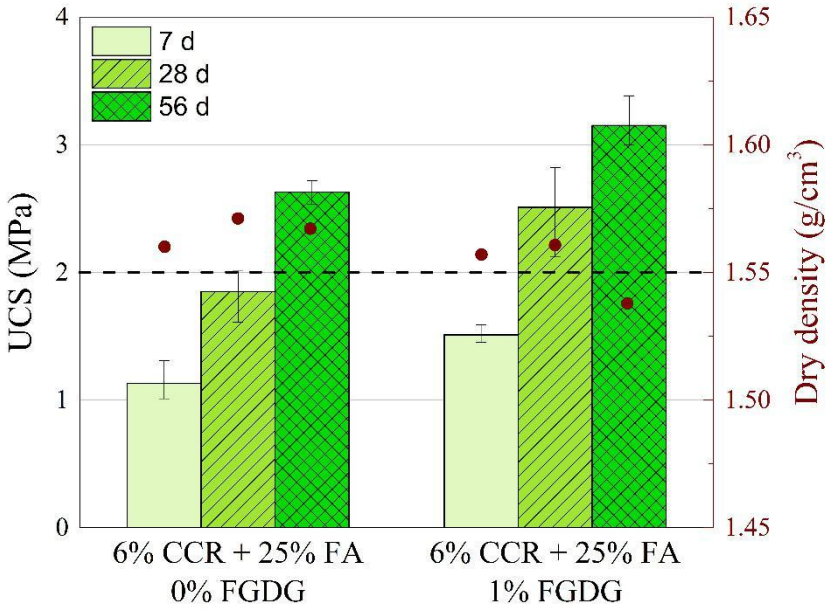

Figure 2. Unconfined compressive strength results at different curing time.

4.2. Microstructural characterization

The thermogravimetric and derivative thermogravimetric curves of samples tested at 7 and 56 days are presented in figure 3. The main weight losses detected in the analyses where: i) the stepwise loss before 100 °C due to water evaporation; ii) the loss occurring at 115-150 °C, attributed to cementitious hydration products (i.e. calcium silicate hydrate and calcium aluminate hydrate gels [16] and ettringite [17]); iii) the losses occurring at 230-330 °C and 330-550 °C associated to the dehydroxylation of the clayey fraction of soil; iv) the loss at 600-700 °C attributed to the decomposition of calcium carbonates. In the very short-term, the samples with and without FGDG did not show any relevant difference except for the lower free water content in the sample containing FGDG. On the other hand, the sample containing FGDG showed at 56 days a considerable higher content of carbonates, probably due to the higher availability of calcium ions with the addition of gypsum in the mixture. Nevertheless, the total amount of hydration products did not seem to be affected by the presence of gypsum in the mixture: both mixtures had a similar amount of hydration products at 7 days and a similar increased quantity at 56 days.

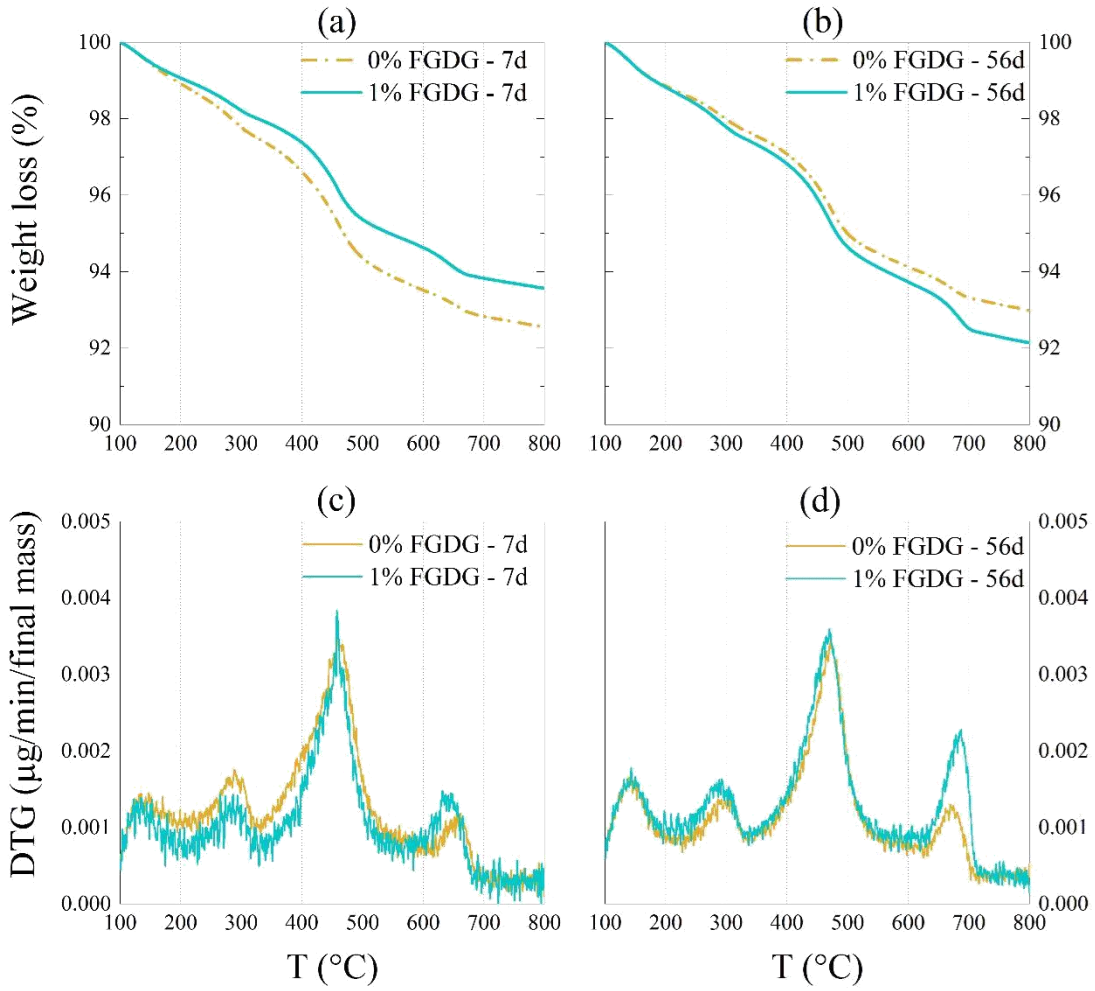

Figure 3. Thermogravimetric (a and b) and derivative thermogravimetric (c and d) results of samples with and without FGDG at 7 (a and c) and 56 days (b and d).

SEM images of samples tested at 7 and 56 days are reported in figure 4. After 7 days most of fly ash particles (recognizable in the figure for their spherical shape) had a smooth surface and they were scarcely incorporated in the matrix. Conversely, at 56 days a larger amount of fly ash particles were characterized by a rough surface, indicating that the amorphous phase composing the shell had partly reacted to form pozzolanic products [18]. Moreover, fly ash particles seemed to be better embedded in the matrix. After 56 days, especially in the sample containing FGDG (figure 4d), ettringite crystals (needle-shaped elements) could be easily spotted. Ettringite is a typical product of Portland cement hydration, resulting from the reaction between calcium aluminate and calcium sulphate [19]. In the studied systems, the presence of sulphates in FA and the addition of gypsum promoted the growth of ettringite crystals in the reference and FGDG-stabilised samples respectively. Nevertheless, energy dispersive spectroscopy analysis on the needle-like elements spotted in the reference mixture after 56 days (figure 4c) should be performed to understand whether they were really ettringite or Type I CSH crystals [20].

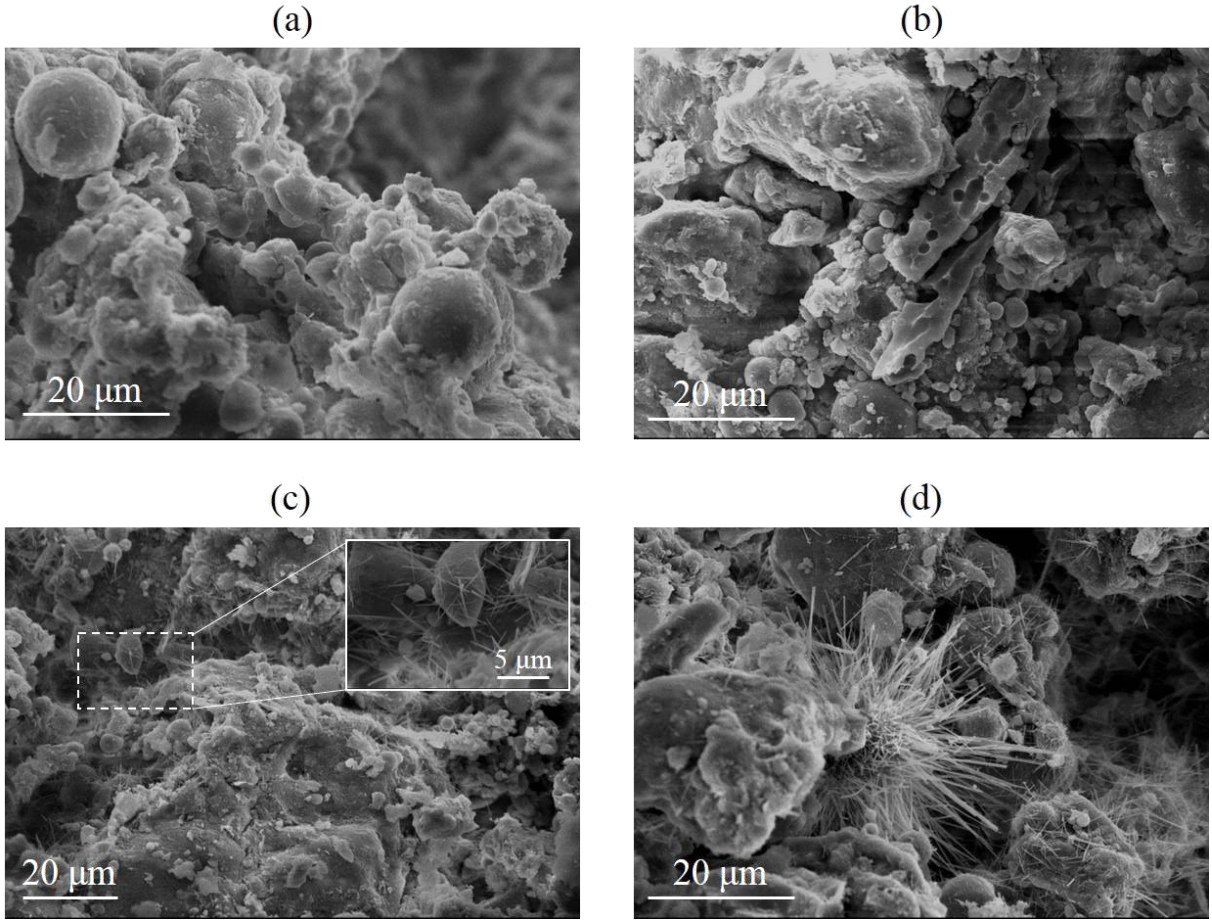

Figure 4. SEM images of samples tested at 7 days (a and b) and 56 days (c and d) for mixtures without FGDG (a and c) and with FGDG (b and d).

5. Discussion

The addition of 1% FGDG to the mixture proved to increase the mechanical properties of the waste-stabilised rammed earth mixture and allowed to reach the 2 MPa limit at 28 days. Although thermogravimetric analyses did not show any significant difference in the amount of hydrated particles in samples containing FGDG, SEM images showed a net increase of ettringite crystals after 56 days. The ettringite crystals most likely filled the voids in the soil matrix and formed a better interlocked structure compared to the base mixture [21]. However, specimens containing FGDG also showed a slightly lower density and a larger volume at 56 days, indicating that the samples underwent expansion after the 28th day. This behaviour was most likely linked to the hydrophilic nature of ettringite.

6. Conclusions

Aim of the present work was to investigate whether the addition of an industrial by-product (i.e. gypsum from flue gas desulfurization) could improve the short-term resistance of a waste -stabilised earthen mix that proved to have an acceptable long-term compression strength but poor early-age resistance. Results showed that adding gypsum from flue gas desulfurization to a calcium carbide residue-fly ash stabilised earthen mixture undoubtedly increased its mechanical resistance, both in the short and in the relatively-long-term (i.e. 56 days). Most importantly, the addition allowed to reach the minimum resistance required by the existing standards for earthen constructions at 28 days. The increase in strength could be ascribed to the fast formation of ettringite in the mixture, which filled the

voids and created a stronger matrix. Nevertheless, the slight expansion the specimens underwent to should be further investigated to understand whether it may generate structural problems in the long-term [22]. A different dosage of gypsum would probably lead to different results both in terms of mechanical performance and volume and could be therefore investigated to find an optimal mixture to maximise the resistance and minimize the expansion.

The extensive use of by-products in the earthen mixture could be beneficial not only for the structural behaviour of the walls, but also for the environment, by reducing waste. Furthermore, the large amount of carbonates detected in the FGDG-stabilised samples suggests that the building material could also act as a carbon sink by removing CO_2 particles from the atmosphere and store them in the matrix [23]. To conclude, the study proved that it is possible to have a rammed earth mixture that meets the strength requirements of the available earthen construction standards both in the short and in the long term, while guaranteeing minimal environmental impacts and fostering circular economy.

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