A reverse engineering approach for low environmental impact earth stabilization technique

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Abstract. The major drawbacks of earth such as low water stability and moderate strength have led mankind to stabilize the earth. It has been developed as a vernacular technique in different civilizations. Since then, the focus was mainly on gypsum, lime, or pozzolan stabilization. Recently, cement has become one of the commonly used additives in earth stabilization, which consequently reduce the environmental advantage of earth. This paper deals with a reverse engineering approach for low environmental impact earth stabilization technique, aiming the replacement of cement in earth stabilization. Various earth-mixtures were done to investigate the performance of this technique. Water contact behaviour and compressive strength of the stabilized earth specimens was determined. Moreover, the characterization of the stabilization effect has been performed through X-ray powder diffraction patterns (XRD) and clearly identify the production of ettringite using very low CO\textsubscript{2} intensive raw materials. Furthermore, the carbon footprint of the stabilized earth-mix has been determined with the help of LCA (life cycle assessment) calculation. The laboratory analyses on this mix-design have proven a high water-resistance and the results show a remarkable increase in compressive strength. Finally, these results open a new avenue for earth stabilization and secure the implementation of this material in the conventional construction industry.

1. Introduction

The discovery that soil can easily be formed and that it can serve as an effective building material responding to the requirements of habitability led to the development of mankind’s oldest building culture. Today, the earthen construction is one of the most common construction techniques in the world and nowadays more than two billion people live in earthen house.\textsuperscript{[1]} In the past, the knowledge about the stabilization effects of various materials against weathering was mostly applied in form of surface protection in earth constructions. Within the variety of materials gypsum, lime, and pozzolanic materials were the most used ones. Today cement as a stabilizing agent stepped forward, however with its environmental impacts. Cement production generates CO\textsubscript{2} emissions from two sources: combustion (38 \%) and calcination (62 \%). Combustion-generated CO\textsubscript{2} emissions are related to fuel use while emissions due to calcination are generated when the raw materials (mostly limestone and clay) are heated and CO\textsubscript{2} is liberated from the decomposed limestone.\textsuperscript{[2]} Calcination CO\textsubscript{2} is directly linked with the clinker production, used for the production of Portland cement. In addition, calcination of cement kiln dust is a relevant source of CO\textsubscript{2} in countries where such dust is discarded\textsuperscript{[3]}.

While we often talk about the environmental problems caused by very energy-intensive sectors, earthen architecture needs to be as stronger as it has been in the past. In the last decade the earthen architecture is getting more and more popular.\textsuperscript{[4]} However, in contemporary earthen architecture, cement is being commonly used to stabilize the earth material. A strategy to substitute cement with environmentally friendly additives is needed. For this purpose, a variety of alternative materials with lower environmental impacts can be used. Their use is based on the importance of minimizing CO\textsubscript{2} emissions, as well as increasing interest in the production of cementitious materials that develop good mechanical properties.
and good stability in corrosive environments[5]. This paper deals with an alternative solution consisting in combining trass, gypsum, and lime (TGL) to replace the use of cement in a vernacular way.

1.1 Stabilization and a reverse engineering

Stabilization is an old tradition, however, it was only in 1920 that a scientific approach could be developed [6]. Today, in countries like the USA, France, Australia, and Spain it is an important research subject, succeeded in testing earthen constructions as a significant alternative against highly energy consuming new products. Since ancient times, small proportions of lime [7], pozzolan and gypsum were used in combination with earth. From the beginning of 1940ies cement became one of the most widely used additives in earth stabilization. For instance, in 1942 only in Karnal, Haryana, India 4000 rammed earth houses using 2.5% cement stabilization [8] were built.

However, today, the building sector tends towards reducing the use of cement or alternative solutions to produce low carbon emitting cement. As it is one of the targets of this study to replace the use cement in earth stabilization, we focused on mechanism of stabilization through examining and analysing the reactions between the stabilizing agents in detail, to see how it works and what was being produced causing the stabilization effect, which was already known in practice since the antient times. This reverse engineering approach helped us to understand how we could replace cement with low carbon emitting additives.

Several studies have tried to explain the effects of pozzolan, gypsum and lime, stabilization. In 1970ies Kafescioglu has investigated the properties of gypsum-lime-earth mixtures and called this mixture as Alker. In 2007, Vroomen [9] researched the properties of cast gypsum-stabilized earth. According to this study, a great advantage of gypsum over cement is that it can be produced locally by small-scale enterprises and it demands a low amount of energy in production as it can be calcined at approx. 125°C instead of 1100°C. In 2011, Lopez et al. [10] studied the chemical reaction between soil, fly ash (15%), gypsum (10%), lime (2%). They stated, when fly ash and lime are mixed with water, there is no chemical reaction in the initial phase. However, with increasing curing time a pozzolanic reaction begins between the fly ash and the gypsum. In 2011 Isik [13] and in 2012, Pekmezci et al. [11] published a paper showing the performance of earth structure by using lime (2,5-5%) and gypsum (8-10%) addition. According to these researches, gypsum-lime stabilization improves the water resistance of earth.

As fly ash has several drawbacks such as seasonally limited production, encouraging the sectors producing by-products of burning processes through its usage and therefore, contributing to environmental impacts, we substituted it with a natural pozzolan called trass.

2. Materials and procedures

2.1. Materials

The earth used for the preparation of stabilized earth specimens consists of 30% commercially available mineral earth material for plastering (Stroba Naturbaustoffe Ag, Switzerland) and of 70% standard sand CEN EN 196-1. The X-ray powder diffraction technique revealed, thanks to Rietveld methods [32,33], that the main mineralogical components are muscovite/illite (24.8wt%), quartz (21.3wt%), kaolinite (21.3wt%) and smectite (16.6wt%). The complete mineralogical composition is given in Table 1.

| Component | Anasrite | Calcite | Chloreclase | Goethite | Kaoilinite | Microcline | Muscovite/Illite | Plagioclase | Pyrite | Quartz | Rutile | Smectite |
|-----------|----------|---------|-------------|----------|------------|------------|-----------------|-------------|--------|--------|--------|---------|
| (%)       | 0.3      | <0.2    | 1.1         | 9.1      | 21.3       | 2.3        | 24.8            | 1.2         | 0.4    | 21.3   | 1.6    | 16.6    |

Three different additives (trass, gypsum and lime) were used in combination to stabilize the earth material. The trass (Tubag, Germany) was used as pozzolanic additive. It is also known as “rheinisher Trass”. Its chemical composition, obtained through X-ray fluorescence spectrometry (XRF), is given in Table 2. Trass is a natural pozzolanic material, which can be found in various regions of the earth. The mineral composition of trass is mainly volcanic glass, zeolitized to a different extent (clinoptilolite), and
plagioclase [12]. XRD pattern of the trass is given in Figure 1. Commercially available hemihydrate gypsum (CaSO$_4$·1/2H$_2$O) was used. Moreover, a hydrated lime (Ca(OH)$_2$) was used as an additive.

**Table 2.** Chemical composition of the trass studied by X-ray fluorescence analysis. Values are given in mass % [13].

| Component, (%) | SiO$_2$ | Al$_2$O$_3$ | TiO$_2$ | Fe$_2$O$_3$ | MgO | Mn$_3$O$_5$ | P$_2$O$_5$ | CaO | SO$_3$ | K$_2$O | Na$_2$O |
|---------------|---------|------------|---------|------------|-----|-------------|------------|-----|--------|-------|--------|
|               | 56.90   | 18.50      | 1.10    | 6.30       | 2.20| 0.2         | 0.2        | 5.20| 0.20   | 5.70  | 3.50   |

**Figure 1.** X-ray diffraction spectrum of the trass used in this study.

2.2. **Sample preparation:**
Four stabilized earth samples were produced by using different proportion of trass, gypsum, lime (TGL), and ordinary Portland cement (OPC). For all samples, the water to binder ratio was determined as 0.4 allowing to obtain a pourable material. The mix samples were poured into standard steel moulds (4cm x 4cm x 16cm). The mixture proportions and labelling of the stabilized earth samples are given in Table 3. After the addition of water, the mixing and the casting of specimens were no longer than 10 minutes. The mixing of the material was done manually. Samples were stored at 23°C and 50% relative humidity. Moreover, to identify the pozzolanic reaction products, XRD analyses were performed on mix-designs mentioned in Table 3. The samples for the XRD analyses were prepared without earth. Therefore, the chemical interaction between additives and clay was not investigated in this study. XRD samples were cured for 7 days at 23°C and 50% relative humidity.

**Table 3.** The labelling and mixture proportions of the specimens

| Labelling Description | PE | T10G8 | T14G4 | T16G2 | T16C4,5 |
|-----------------------|----|-------|-------|-------|---------|
| Plain earth with 30% terrassol and 70% standard sand | Earth with 10wt% trass, 8wt% gypsum and 2.5 wt% of lime | Earth with 14wt% trass, 4wt% gypsum and 2.5 wt% lime | Earth with 16wt% trass, 2wt% gypsum and 2.5 wt% of lime | Earth with 16wt% trass, 4.5wt% Ordinary Portland cement |

2.3. **Procedures**
The pozzolanic activity can be determined by physical, chemical, or mechanical means. In this research, together with the water insertion test, the compressive strength (mechanical method) and XRD analysis (physical method) have been conducted to determine the pozzolanicity of the proposed mix-design. To
done. The water insertion was carried out according to the standard DIN 18945. The specimens were cured at 23°C and 50% relative humidity for 14 days. The loss of material was determined by filtering the residue in the dip tank. 7 and 28-day compressive strength tests were carried out on prismatic specimens with the dimensions of 40 x 40 x 160 mm. Mineralogy of the samples is determined on randomly oriented powder specimens with X-ray diffraction analysis [14]. X-ray diffraction measurements were made using a Bragg-Brentano X-ray diffractometer (D8 Advance, Bruker AXS, Germany) using CoKα radiation. The qualitative phase analysis was carried out with the software package DIFFRACplus (Bruker AXS) [15].

3. Results and discussions

3.1. Water Contact Tests:
One of the main decaying factors in earth constructions is the presence of water. Once plain earth gets contact with water, it swells, and the dissolution and erosion are inevitable. To overcome this weakness, stabilization of earth can be a significant application. The loss of mass of the stabilized earth specimens and plain earth after the water insertion test is plotted in Figure 2. According to the water insertion test described in DIN 18945, the loss of mass has to be less than 5% of the total mass to be considered as acceptable. After 10 min. of water insertion, the loss of mass of the plain earth samples was determined as 38.406% of the total mass. However, as can be seen in Figure 2, all stabilized earth samples have shown similar behaviour and the loss of mass of all stabilized series is between 0.02-0.03 percent of total mass, which is significantly lower than the limit value. Moreover, no cracks were observed due to swelling: the proposed combination of additives significantly improved the water stability of the earth specimens. However, it can be observed that the change in trass/gypsum ratio does not influence the water resistance of the stabilized earth specimens.

![Figure 2. Loss of mass of stabilized earth samples after water insertion test.](image)

3.2. Compressive strength:
In order to prove that the proposed TGL stabilization can be used for substitution of cement stabilization, together with TGL stabilized specimens, a series of cement stabilized specimens were also prepared for compressive strength test. The 7 and 28-days results of compressive strength tests of stabilized earth specimens are shown in Figure 3. As can be seen in Figure 3, the maximum compressive strength is obtained for T16G2 samples containing 16wt% of trass and 2wt% of gypsum. While T10G8 containing the highest amount of gypsum does not show an increase in compressive strength from 7 to 28 days, the samples prepared with a higher amount of trass progressively gain strength from 7 to 28 days. Using higher content of trass allows improving the compressive strength of stabilized earth materials.
Furthermore, as can be seen in Figure 3, the compressive strength of cement stabilized specimens do not show an improvement from 7day to 28day and the value is averagely 2.5 MPa. This value is closed to the values of other researches related to cement stabilized earth. For instance, Ciurileanu et al. (2012), earth 5% cement, 2.44 MPa [16], Waziri, B. et al. (2013), earth with 5% cement, ca. 2.5MPa [17], Sofi et al. (2016), earth with 6% cement, 2.75MPA [18].

3.3. XRD Analyses:
The mechanism of stabilization is based on pozzolanic activity, which causes a durability effect in an environmentally friendly way. To better understand this mechanism and to identify the products of pozzolanic reactions, the mineralogical composition of the mix-designs was analysed with the help of X-ray diffraction (XRD). The XRD results of 7day cured mix-designs are given in Figure 4. As can be seen in the XRD pattern, the sample with 10 wt% of trass and 8 wt% of gypsum (T10G8) displays high amounts of gypsum. As expected, the intensity of gypsum peaks is being reduced by increasing the amount of trass. Very weak peaks of ettringite can be observed in T10G8. However, it can be noted that, with the increasing amount of trass in samples, the intensity of the ettringite peak is getting higher. The reason for this behaviour is assumed to be the pozzolanic effect of trass. The chemical additives react with particles of trass to produce hydration products such as ettringite (Ca₆Al₂(SO₄)₃(OH)₁₂·26H₂O). A part of Aluminium is being consumed by the formation of ettringite. The cement specimens were not investigated with XRD analyse. However, as it is known, the ettringite is the typical reaction product of cement responsible for the strength and stability.
Figure 4. XRD pattern of the studied mixes of additives (without earth). (E; Ettringite, G; Gypsum, A; Analcime, Q; Quartz, C; Calcite)

4. Carbon Emission of mix-design

The construction industry is a large contributor to CO\textsubscript{2} emissions, with buildings responsible for 40% of the total European energy consumption and a third of CO\textsubscript{2} emissions [19][20]. One of the corresponding EU targets for sustainable growth is the reducing greenhouse gas emissions by 20% compared to 1990 levels by 2020 [19]. In respect to the EU target, the aim of earth stabilization with TGL addition is to replace the use of cement in earth stabilization and therefore, to reduce the cement-related CO\textsubscript{2} emission.

The carbon emission of trass in the proposed earth-mix is assumed to be almost zero, as trass is just a pulvèrisèd natural pozzolanic earth. The only carbon emitting agents are, therefore, gypsum and lime. For this reason, the total amount of gypsum and lime (4.5wt%) was replaced with cement.

Where the carbon emission of gypsum is about 100 kgCO\textsubscript{2}/kg, this value is about 600 kgCO\textsubscript{2}/kg for lime. On the other hand, the carbon emission of cement is closed to 700 kgCO\textsubscript{2}/kg.

In this respect the proposed mix-design with 2% gypsum and 2.5% lime is 1.9 times less carbon emitting then a cement stabilized one.

5. Conclusions

This paper focuses on the stabilization effect of TGL(trass (pozzolan) + gypsum (CaSO\textsubscript{4} \(\frac{1}{2}\)H\textsubscript{2}O) + lime (Ca(OH)\textsubscript{2})) system on the mechanical and physical properties of the unfired earth, as a vernacular solution to replace the use of cement in earth stabilization. The results can be summarized as follow:

1. The water-resistance and the compressive strength of the plain earth were improved by the presence of trass, gypsum and lime.
2. Ettringite, which is typical hydration product of Portland cement, could be produced with the proposed mix design, in a more environmentally friendly way.
3. The carbon emitting of the proposed earth stabilization is 1.9 times less than cement stabilization.
4. With the proposed stabilization, with only 4.5% of carbon emitting additives (2% gypsum +2.5% lime) a compressive strength value of 6 MPa could be achieved after 28 days. However, this value was only 2.50 MPa by cement stabilization.

Finally, the results show that earth stabilization with low carbon emitting additives can even be much more efficient than cement stabilization. However, the sources of natural pozzolanic earths on the world need the be discovered ones again with the help of new technologies as there is still lack of information related to these sources and of availability.

6. References

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