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Development of a lime based grout for cracks repair in earthen constructions

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HIGHLIGHTS

- A grout based on hydraulic lime mortar for the cracks repair of earthen constructions was developed.
- A lime based grout for earthen material strengthening requires low water content, good water retention and low shrinkage.
- The lime based grout developed is adaptable to the strength properties of earthen substrate.
- Results showed a satisfactory performance concerning fresh and hardened mortar properties as well as injectability.
- Grouting, as isolated intervention, is not a viable repair method if a structure will be exposed to shear or tensile loads.

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ABSTRACT

The study presents the results from the development of a grouting material based on hydrated lime with addition of pozzolana, which is referred to as hydraulic lime, suitable for the repair of cracks in a variety of earthen building techniques. The goal was to develop a material also compatible with earthen structures exposed to dynamic loads. The grouting mortar was designed to be adaptable in strength properties and at the same time to have sufficient robustness for preparation and use on the construction site. Results showed a satisfactory performance of the grout concerning fresh and hardened mortar properties as well as injectability.

1. Introduction

Earthen materials have very low strength values and are highly sensitive to changes in load and deformation [1–10]. Historic earthen materials are often affected by material loss caused by erosion or by the activity of insects or smaller mammals. Back erosion and animal burrows reduce the load bearing capacity of the walls and are clearly a weakening factor during earthquakes [11,12]. Termite infestation, for instance, was assumed to be a key factor leading to the collapse of some parts of the Bam Citadel in Iran in 2003 [11]. Frequently cracks in earthen structures are insufficiently or inappropriately repaired because of lack of knowledge and/or technology.

Mineral based grouts are used to repair cracks in earthen construction to re-establish structural continuity but can also be used to fill smaller voids and gaps. Structural grouting is usually complementing other strengthening techniques such as the introduction of reinforcement meshes or tie-rods. In particular, the behaviour of cracks repair by grouting poses a challenge in earthen materials and demands specific requirements for the grouting mortar. Grouts require a good workability, low shrinkage, a good bond to the original material, chemical and mechanical compatibility and durability [13].

Grouts discussed in literature are composed primarily of modified soil with the addition of stabilisers, such as lime [14], hydraulic lime [15] or cement [16]. Additional additives consist of deflocculants, aggregates or fibres to reduce shrinkage and to increase strength and adhesion. Warren [17] provided a general summary of grouts for earthen materials. The grouting methodology for earthen materials is mostly based on gravity flow or on low-pressure pumping systems. A practical example for structural grouting of earthen structures is the Pio Pico Adobe in California, USA [18]. This building was repaired in 1991 with an earth-fly

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ash grout and suffered only little damage during the Northridge Earthquake in 1994.

While more recent studies presented the effectiveness of grouting for historic brick and stone masonry [19–23], the structural performance of grouted earthen buildings depends on the shrinkage/swelling behaviour and the bond of the grout [13]. Stone or clay brick masonry can be wetted prior to grouting, which prevents loss of moisture in the grout and which greatly increases the bond between grout and stone. This cannot easily be done with earth due to its sensitivity to liquid water. In particular lime based grouts cannot fully retain their water content and dry out prematurely due to water uptake of the earthen substrate. This usually causes cracking within the grout/earth interface. The water retention of earthen grouts, however, is higher than the capillary absorption of the earthen substrate and earthen grouts are therefore less prone to loss of moisture. On the other hand they show higher shrinkage values, which may result in internal cracking and loss of strength. Therefore, the determination of suitable water/binder ratios and water retention values for lime and hydraulic grouts and the water/soil ratio for earthen grouts are critical factors as far as shrinkage behaviour, bond and mechanical performance are concerned.

In the case of earthen structural elements, as is the case with other types of masonry, existing literature suggests that stiffness discontinuity can cause global damage when the structure is subjected to seismic loading [11]. The use of highly rigid mortars or grouts [19] may create stiffness discontinuities in the masonry, which, in case of seismic loading, may result in stress concentration and crack formation. It is therefore recommended not to use very stiff materials in the repair or strengthening of earthen buildings, since even small stress concentrations suffice to cause damage [24].

Challenges in the grouting of earthen structures are good bond, long-term performance and the restoration of long lasting structural integrity and continuity of a damaged structure. The general design of a grout has to take into account properties such as water retention, shrinkage, durability, adhesion, mechanical strengths and chemical compatibility. In addition, grouts have to be sufficiently work- and flowable to fill small cracks and voids without segregation or bleeding. Therefore, the rheological behaviour has to be well understood and controlled to gain the desired effects [20].

The repair of earthen buildings is most usually done with earth as a repair material by stitching or exchange of earth blocks (in adobe structures). The repair of cracks is traditionally done by stuffing manually mortar into the gap. Naturally, this method is only usable for cracks with large widths. Another disadvantage is that cracks going through thicker walls cannot be completely reached by the tools used for stuffing the mortar into the crack. Lime based grouts for earthen materials were usually used for re-attachment of plasters but less for structural reasons [25,26].

Due to the nature of earthen materials grouts based on formulated or hydraulic lime (according to the definition in EN 459-1 [27]) have to meet considerable demands on a variety of properties, which are related to injectability, compatibility and durability. The goal of this study was to create a grout, which can be used to re-establish structural continuity in cracked earthen masonry or other massive earth walls (rammed earth and cob) with the focus on grouting cracks. The grout material was based on hydrated lime (calcium hydroxide) with additions of pozzolana and limestone filler.

2. Methodology and materials

2.1. General approach and grout requirements

According to intervention requirements the constituents of the grouts have to be compatible and durable with each other and with the original materials [28]. The grout must also provide the required mechanical strength, which has to be adjustable in case of repair of earthen materials. Therefore it is reasonable to use earthen material binders [13,29] or binders based on hydraulic lime [30]. Grouts based on cement are rather inappropriate due to the potential lack of chemical and mechanical compatibility with the earthen substrate. Usually organic binders (resins) are inappropriate as well since their higher strength and stiffness might cause stress concentration resulting in damage of the original earthen material.

Grouts based on earth exhibit a variety of disadvantages: the shrinkage may be too high [13,17], strength is low and there is no control on strength development and, when using natural earth, its quality is difficult to control. In particular the last point has to be addressed carefully since small variation in the composition of the clay fraction of the earth can have a strong impact on its injectability, adhesiveness and strength.

The concept of the development of a suitable grout in this work was therefore based on hydrated lime with addition of pozzolana, which is referred to as hydraulic lime according to EN 459-1 [27]. Lime based grouts have a variety of advantages:

- the quality of the starting materials is within a narrow window (when using industrially produced materials);
- the grout mix can be adjusted to achieve appropriate physical and mechanical compatibility to the earthen substrate;
- chemical compatibility can be controlled by using appropriate starting materials;
- the durability is at least as high as that of earthen materials.

However, of paramount importance is the adhesion of the interface between lime grout and earth that depends on a variety of variables, e.g. condition of the crack surface, porosity of the earth, water retention of the grout. For the actual grout development a set of target specifications was therefore defined. Table 1 gives an overview of the required properties of the grout.

2.2. Mix components

It was important to use materials, which are readily available, cheap and industrially standardised in terms of quality. The following materials have been chosen for the development of the grout mixes:

Table 1
Desired parameters and criteria to be fulfilled for grouting cracks in earthen masonry.

Property	Qualitative description	Parameters
Flow value (Hägermann cone)	High	$\geqslant$25 cm
Water retention	High	>95%
Adhesion (pull-off)	Good	>0.05 MPa
Young's modulus	Compatible with earthen substrate	<1500 MPa
Compressive strength	Compatible with earthen substrate	<4 MPa
Chemical and mechanical compatibility	Good	No salts efflorescences