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A lime-based grouting material for the repair of earthen structures

The repair of earthen structures is not an easy task. Earth as a construction material has comparatively weak mechanical properties. It is also susceptible towards liquid water, were it can lose cohesion very quickly if certain moisture contents are exceeded. Repair concepts of structures built with such materials are therefore challenging. Historical earthen structures often exhibit damages in form of extensive cracking, which may have been caused by static or dynamic loads. Frequently these cracks are insufficiently or inappropriately repaired because of lack of knowledge and/or technology. In particular, the behaviour of crack repair by grouting poses a challenge in earthen materials and demands specific requirements for the grouting mortar, such as low water content, good water retention, low shrinkage. Grouting materials require additional specifications such as compatible strengths and Young's modulus as well as good adhesion to the earthen substrates. In addition, grouts have to be sufficiently 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 [1].

The repair of cracks in earthen buildings 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 [2] [3].

Due to the nature of earthen materials grouts based on formulated or hydraulic lime (according to the definition in EN 459-1 [4]) have to meet considerable demands on a variety of properties, which are related to compatibility, durability and in particular to the ability of being injected. 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 lime stone filler.

Methodology and materials

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 [5]. The grout must also provide the required mechanical strength, which has to be adjustable in case of repair of earthen materials. The concept of the development of a suitable grout in this work was therefore based on hydrated lime with addition of pozzolana. 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;
- 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.

Property	Qualitative description	Parameters
Flow value (Hägermann cone)	High	≥ 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 salt efflorescences

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

Mix components

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

- industrial lime hydrate (CH);
- silica fume (SF);
- class F fly ash (FA);
- limestone filler (LS).

To achieve the desired grout properties essentially two admixtures were used:

- super plasticiser on the basis of polycarboxylate ether (PCE) to increase flowability;
- kaolin powder to increase water retention.

Linen fibres were used as a reinforcement option to increase mechanical performance and to limit cracking. The targeted mechanical properties of the grout were adjusted to the low strength characteristics of the earthen substrate and in particular, its Young's modulus.

Test methods

Table 2 shows the test procedures for the characterisation of fresh and hardened mortar properties. Durability tests were not employed at this stage. The resistance of earth itself to cycles of wetting/drying, freezing/thawing or salt crystallization/dissolution is very weak and under direct exposure to these mechanisms most non-stabilised earthen materials will fail after only a few cycles. The focus of the study was therefore laid on testing the mechanical behaviour of the grout and grouted earthen materials. The chemical compatibility was ensured by the use of starting components, which contained no or only minor amounts of releasable ions (e.g. Na^+, K^+, SO_4^{2-}). Details on the characterisation of fresh and hardened mortar properties are reported in a previous study [6]. The efficiency of grouting was tested by diagonal compression tests on cob panels before and after grouting. Details of the tests are reported elsewhere [7].

Table 2. Test procedures

Property	Standard, test procedure
Apparent density of the single components	He-Density DIN 66137-2 [8]
Phase composition of single components	Powder x-ray diffraction (XRD)
Chemical composition of single components	X-ray fluorescence analysis (XRF)
Particle size of single components	Laser granulometry
Reactivity of pozzolanic components	Isothermal calorimetry
Optimum packing density and water demand of different mixes	Puntke tests [9]
Setting time	VICAT penetration (EN 196-3) [10]
Drying shrinkage of grout	DIN 52450 [11]
Flow consistency of fresh grout	EN 1015-3 [12]
Compressive and flexural strength of hardened grout	EN 1015-11 [13]
Apparent density of hardened grout	EN 1015-10 [14]
Adhesion strength (on earth block)	EN 1015-12 (modified) [15]
Water retention	EN 413-2 [16]

Material	Main characteristics
Calcium hydroxide (industrial grade)	Main component: $Ca(OH)_2$, traces: calcite
Silica fume (SF)	Main component: amorphous SiO_2; traces: carbon
Fly ash (FA)	Main components according to EN 450-1 [17]: glass, minor: quartz, mullite, maghemite
Limestone filler (LS)	Main component: calcite, traces: quartz, feldspar
Super plasticizer	On basis of polycarboxylate ether (PCE)
Kaolin powder	For increasing water retention; main component: kaolinite, minor: quartz, feldspar, mica
Fibres	Maximum fibre length: 5 mm; type: linen

Table 3 Type of materials used for grout mixtures

Mix	Calcium hydroxide (CH)	Silica fume (SF)	Fly ash (FA)	Limestone filler (LS)	Water/solid ratio (by mass)
4	22.5	7.5	20	50	0.30
5	13.5	4.5	12	70	0.30
6	12.0	3.0	15	70	0.30

Table 4 Design of the initial grout mixes 4, 5 and 6 in mass-%

Results and discussion

Raw material data and development strategy

Table 3 shows the characteristics of the components used for the grout mixture.

For the development of a grout formulation, adequate mix proportions of the four basic components needed to be defined. This definition was approached by finding a composition with minimised water demand. The Puntke test method [9] provided a quick and easy tool for measuring the minimum water content of a granular material just before it plasticises.

From the Puntke tests six different mix proportions were created. From these six mixes, three with the lowest water demand were chosen for further in-depth studies (Table 4). Mix 6 showed the lowest water demand in the Puntke tests.

The flow properties of the grouts were essentially balanced via the water/solid ratio and the amount of superplasticiser (SP). In Fig. 1 flow values of mix 6 for two different w/s ratios (with and without fibres) are plotted against the SP content.

The results show that up to a certain amount of SP changes in flow are minimal. From this specific SP

Fig. 1 Flow of grout vs. amount of super plasticizer (mix 6) for two different w/s ratios and at w/s = 0.3, with and without linen fibres.

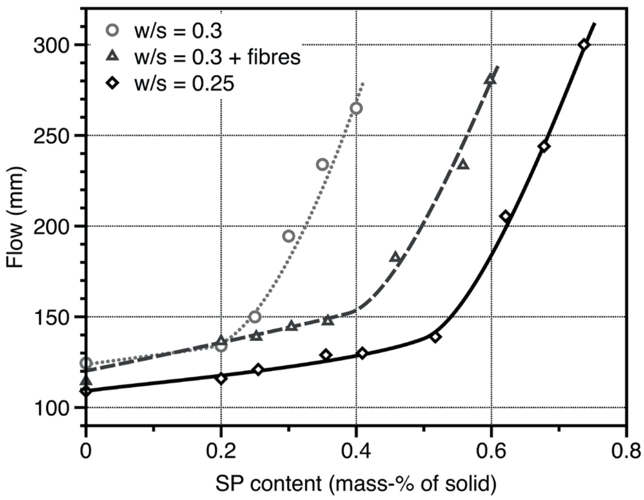
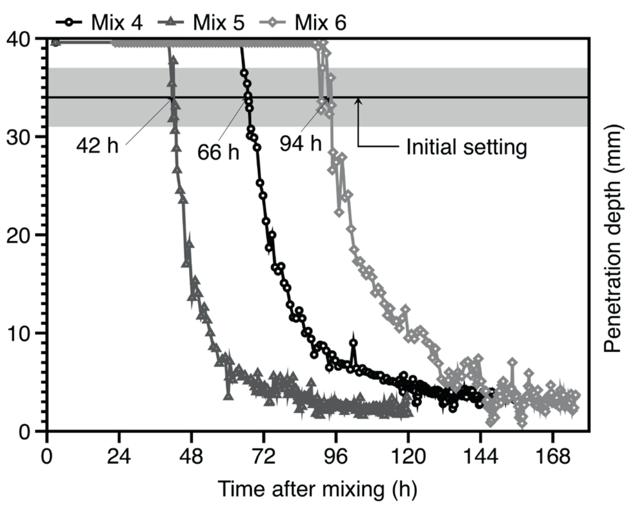


Fig. 2 Results of setting tests for mixes 4 to 6, all prepared with w/s = 0.3



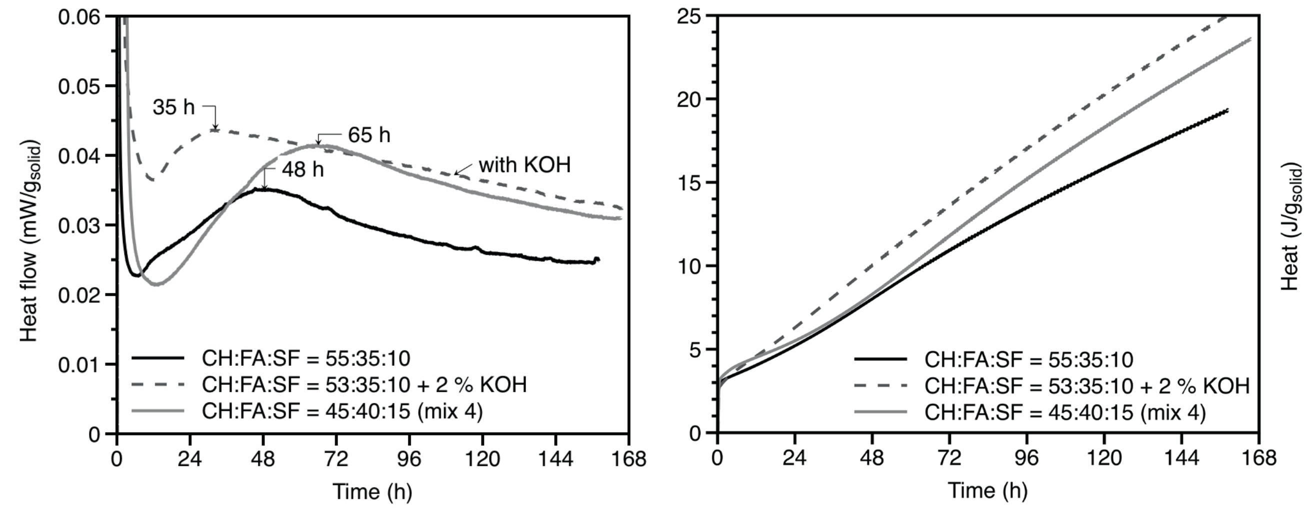


Fig. 3 Heat flow (a) and cumulative heat (b) curves from isothermal calorimetry. The numbers in the legend reflect the mix proportions used (in mass-%).

amount the flow of the grout mixes increased more drastically. A lower w/s ratio led to a reduced flow and a higher demand of SP. Fibres increased the amount of super plasticiser needed to improve the flow. From the flow test results the amount of super plasticiser was set to a range of 0.4 to 0.7 mass-% of the dry grout with a water/solid ratio of 0.30, which enabled a good control of flow and injection within the desired consistency range. Flow tests with different amounts of fibres resulted in an optimum fibre content of 0.2 mass-% of solid.

Results on basic properties

– Setting time

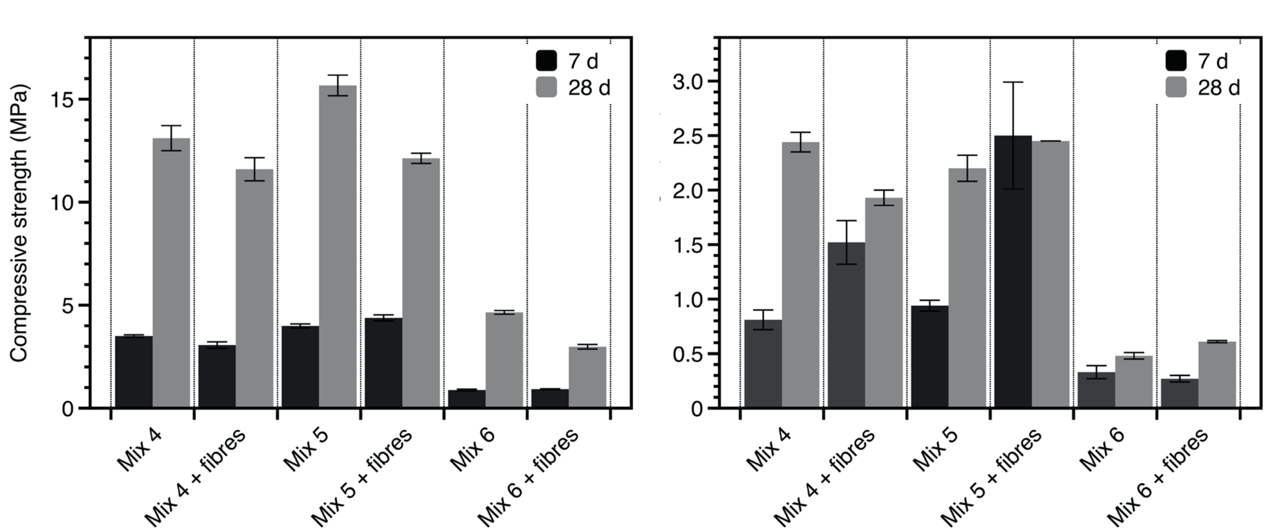
For all mixes the w/s ratio was 0.30 and consistency was adjusted to a flow value of 25 cm by dosing the appropriate amount of superplasticiser. Fig. 2 illustrates the results of the setting time tests for the mixes 4, 5 and 6.

The results show that initial setting started after 42, 66 and 94 hours, respectively. The fairly long setting times were not considered as a problem for the grouting material. The different setting times of mix 4, 5 and 6 were influenced by the different amounts of silica fume (SF), lime hydrate (CH) and fly ash (FA) used in the mixes. Mix 6 with the lowest content in SF and intermediate FA content (Table 5) showed therefore the slowest setting. Mix 4 and 5 had the same SF/CH ratio (= 0.33) but mix 5 set fastest due to its low FA content.

To assess the reactivity of the pozzolana silica fume (SF) and fly ash (FA) the reaction heat of paste samples with lime hydrate (CH) were measured by isothermal calorimetry (ratios in mass-%). This included three sample pastes with the following proportions:

- CH:FA:SF = 55:35:10;
- CH:FA:SF = 53:35:10 and 2% Pot. Hydroxide KOH;
- CH:FA:SF = 45:40:15 (mix 4).

Fig. 5 Compressive and flexural strengths of mixes 4 to 6



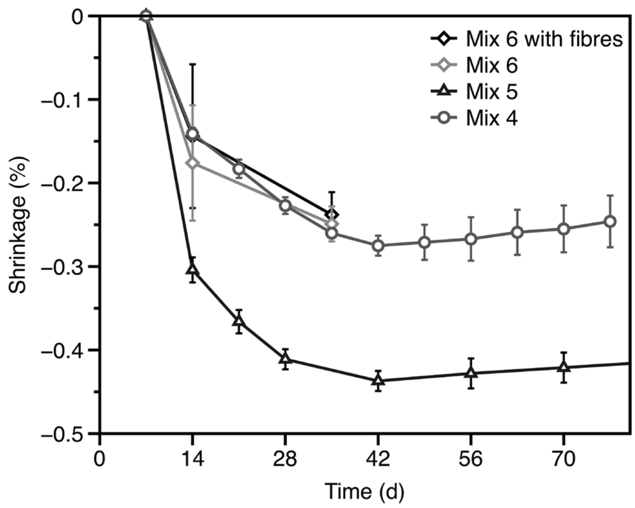


Fig. 4 Drying shrinkage curves of mixes 4, 5 and 6 (average of 6 samples, error bars give standard deviations).

Fig. 3 illustrates the heat flow (a) and cumulative heat curves (b) of the three mixes. The binder with a lower CH and higher SF and FA content (mix 4) showed a more pronounced dormant period and a steeper acceleration period, even though the total cumulative heat of hydration was higher than that of the mix with lower SF content. The peak of the hydration reaction of mix 4 approximately coincides with the initial setting time (Fig. 2 and 3). This indicates that higher amounts of SF and FA increase the total hydraulic reaction but not necessarily speed it up.

– Drying shrinkage

The shrinkage curves (Fig. 4) showed highest values for mix 5. Mix 4 and 6 showed approximately the same shrinkage behaviour.

However, after 28 days the shrinkage of all mixes was below 0.5%. Fibres in mix 6 contributed to a reduction in shrinkage of only about 5%, compared to the same mix without fibres. From the results, it is evident that despite the fineness of the grout the drying shrinkage is not as excessive as in the case of earth grouts. For comparison: a purely earthen grout would have a much higher shrinkage. For earth plaster, it is known that the shrinkage of material with a high content of fines is in the range of 1 to 5% [18].

– Mechanical properties of the grout mixes

Flexural and compressive strengths for mixes 4, 5 and 6 are shown in Fig. 5. The tests were performed on specimens with and without linen fibres. The development of compressive strength showed high values for mixes 4 and 5 after 28 days. However, mix 6, which had a lower content of silica fume, exhibited a significantly lower strength. Fibres reduced compressive strength after 28 days in all mixes. Flexural strength after 28 days was only slightly increased in mixes 5 and 6. Mix 4 was reduced in flexural strength after 28 days compared to specimens without fibres. Fibres, however, were significantly improving the post-peak stress-strain behaviour (ductility) of the grout (Fig. 6).

Fig. 7 represents a comparison of mechanical properties for earth block masonry, rammed earth and cob [7] with the data of the grout mix 6. It follows that mix 6, both without and with fibres falls into the compressive strength range of all three typical earth-construction typologies. Therefore, only mix 6 was considered as mechanically compatible with earthen materials.

Fig. 6 Example of flexural stress-strain curves for mix 6 with and without fibres.

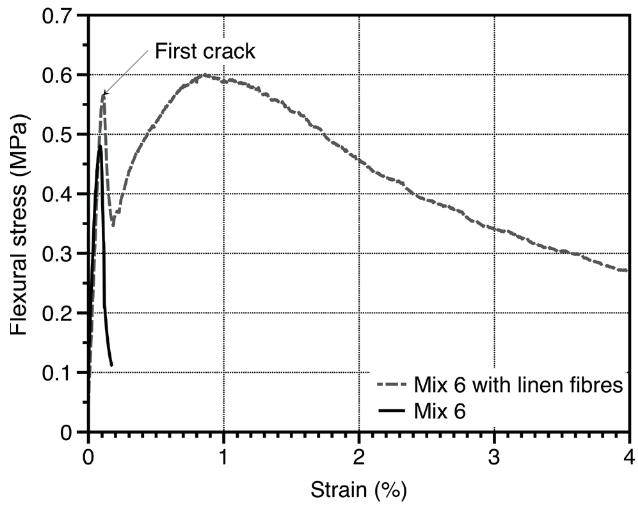
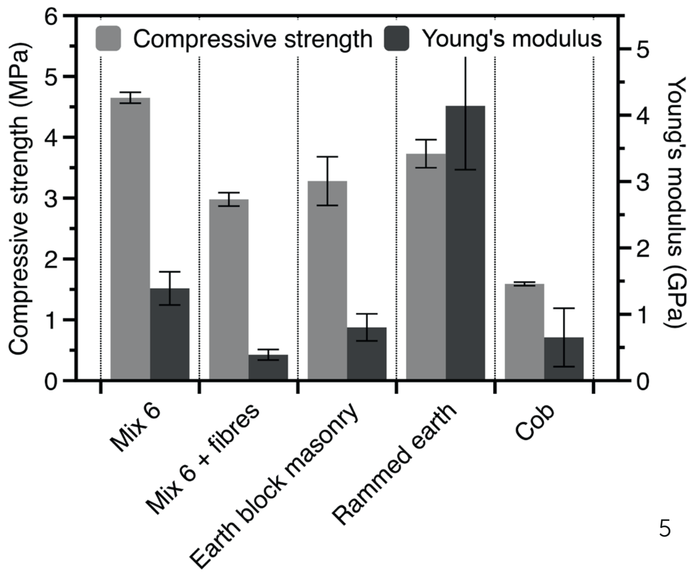


Fig. 7 Comparison of mechanical properties of grout mix 6 with different earthen building typologies.



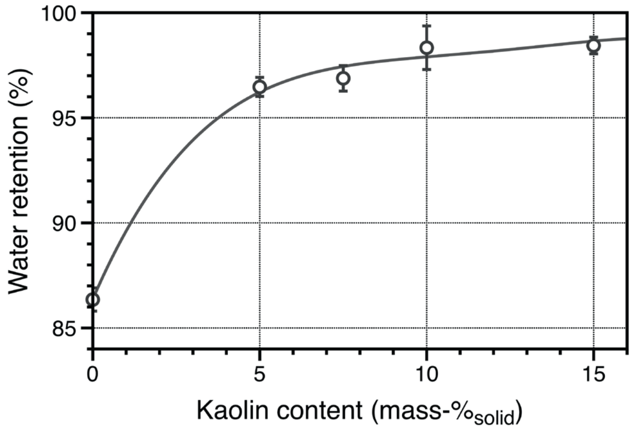


Fig. 8 Increase in water retention of the grout mix 6 (without fibres) due to the addition of kaolin powder

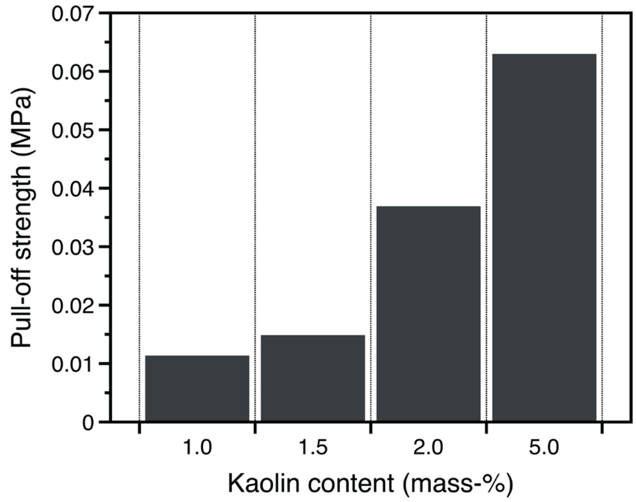


Fig. 9 Pull-off strength vs. the kaolin content of the dry grout (dry mix)

– Water retention and adhesion strength

Water retention of a grout is critical for the bond behaviour towards its earthen substrate. If the retention is low, water is sucked out of the grout causing high shrinkage and cracking in the grout-substrate interface with a loss in bond strength. Hydraulic lime grouts may also have not enough remaining water for the pozzolanic reaction resulting in incomplete hydration and a low overall strength.

To control water retention in the grout an additive in the form of kaolin powder was used. Results of water retention tests performed on mix 6 showed that only 86% of the water can be retained in the grout without kaolin (Fig. 8). With 10 mass-% kaolin water retention increases to 98 mass-%. With increasing water retention, adhesion strength was also improved as the results of the pull-off tests show (Fig. 9).

Table 5 Mix design of the grout

Component	Bulk density kg/m³	Content g/kg	Content kg/m³
Calcium hydroxide	2240	106	196
Silica fume	2000	46	85
Fly ash	2220	106	196
Limestone filler	2750	458	846
Kaolin	2370	46	85
Water	1000	230	425
Superplasticiser	1050	8	15
Total	–	1000	1846

Final grout formulation

The final composition of the grout was based on the previous results and is given in Table 5.

According to EN 459-1 the material can be labelled as hydraulic lime HL2. The addition of fibres controls cracking of the grout and can be added optionally for grouting of cracks larger than 5 mm. Since they usually reduce the flow capacity of the grout, adjustment of the amount of super plasticiser might be necessary, without increasing the water content. The properties of the fresh and the hardened grout are summarised in Table 6.

Table 6 Properties of fresh and hardened grout (numbers in brackets are standard deviations).

Property		Curing time dd	Value
Spread flow diameter	cm		25
Bulk density	kg/m³	7	1863 (20)
		28	1657 (16)
Compressive strength	MPa	7	0.88 (0.04)
		28	4.65 (0.09)
Flexural strength	MPa	7	0.33 (0.06)
		28	0.48 (0.03)
Young's modulus	MPa	7	60 (10)
		28	1390 (250)
Pull-off strength	MPa	12	0.06
Drying shrinkage	%	7	0.18
		28	0.25

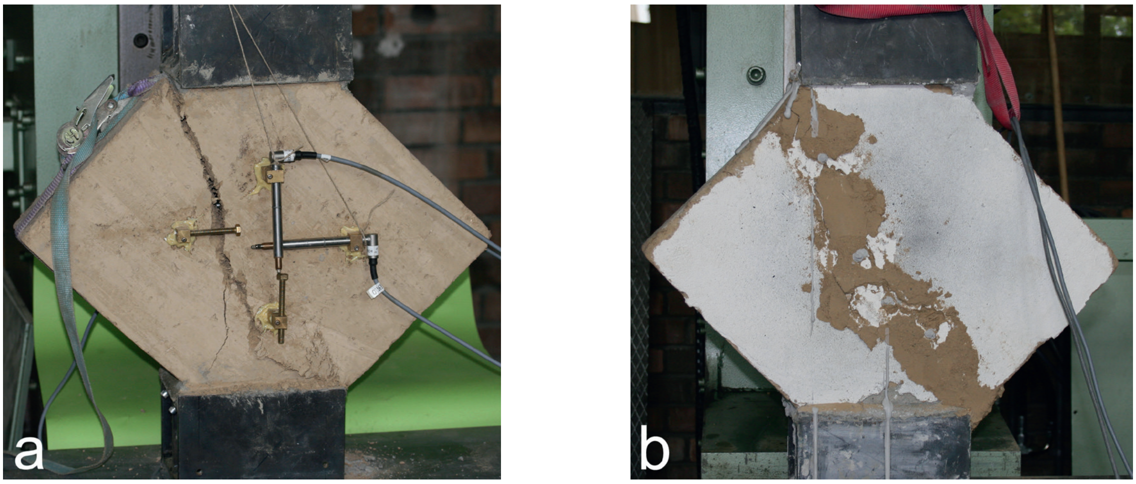


Fig. 10 Cob wall panel after diagonal compression test (a) and after grouting (b)

Grouting of cracks in earthen test specimens

The developed grout formulation was tested on earthen specimens consisting of cob wall panels. Cob was produced by mixing earth with straw and water to a plastic mass. Cracks were induced to the wall panels by diagonal compression tests according to ASTM E 519-10 [19] and consisted mostly of one main crack with some smaller side branches (Fig. 10a). The next step was to close all crack openings with gypsum and earthen plaster (Fig. 10b) to prevent leakage of grouting material. Details of samples preparation are reported in [6].

To see how much of the shear strength τ of a repaired cob panel can be retained compared to the original shear strength, specimens were subjected again to a diagonal compression test. After grouting the cob panels were cured for at least 28 days at 23°C and 50% RH. In total four original and two repaired cob panels were tested.

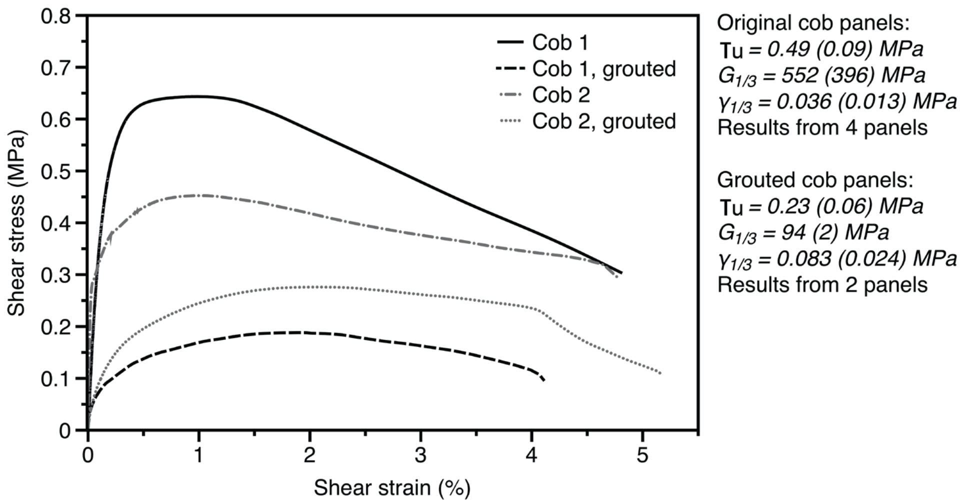
The test on the repaired cob panels showed that the failure occurred in the grouted cracks but additionally new cracks opened up. The main crack surfaces showed a fine layer of grout indicating a good distribution of the grout within the crack system.

Results obtained from the diagonal compression tests are given in Fig. 11 comparing original and repaired cob panels. The shear strength of the repaired cob panels was clearly below the values of the original ones. In one case it reached 20% of the values of the original panel, in the other case 45%. The repair of the panels was performed with a grout not containing fibres. Introduction of fibres may increase the shear resistance within the grouting mortar, however, further studies need to be performed.

Conclusions

The results of this study showed good properties of the developed grout based on hydraulic lime. Criti-

Fig. 11 Stress-strain curves of original and grouted cob panels under diagonal compression. τ_u = shear strength, $G_{1/3}$ = shear modulus, and $\gamma_{1/3}$ = shear strain, both measured at 1/3 maximum load



cal parameters were strength development, shrinkage, water retention and bond behaviour of the grout, which can be adjusted sufficiently to suit most of the earthen materials. Requirements in strength of the grout can be matched by slightly changing the amount of silica fume (in this case strength tests must be performed for control). Flow properties of the grout may vary if starting materials from different sources are used. This variation concerns mostly class F fly ash and limestone filler, which can have a rather large variation in particle size, and thus water demand, depending on the source. In any case, adjustments to the flow must be done by adjusting the amount of super plasticiser and subsequent flow tests, e.g. with a Hägermann cone, which can even be performed in the field. The injection tests showed a good performance of the grout. Large cracks were completely, and cracks with a width < 0.5 mm at least partially filled.

From the mechanical tests it can be concluded that grouting alone is not a viable repair method if a structure is exposed to shear or tensile loads. In these cases, additional interventions such as a polymer mesh reinforcement wrapping the wall [20], glass fibre-reinforced polymer strips [21] or corner keys to interconnect perpendicular walls [22] are required. Grouting functions then as a means to redistribute the loads equally through all parts of a structural element and the reinforcement.

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