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Evaluating the physical and mechanical properties of earth plasters with cow dung – a vernacular solution for earth building in Brazil

In various parts of South America there is evidence of constructions made using earth building techniques by ancient civilisations that reach back thousands of years. In Brazil, however, it is believed that earth building technologies were introduced during the colonial period (from the early 6th century), as there is no evidence that natives indigenous to Brazil used earth as a building material (Rezende et al., 2013).

Since then, earth construction has spread across the country and is still practiced today. Over the years, various additives have been employed to make earth constructions more resilient, with air hardening lime being consider one of the most compatible stabilisers for clay-based earth structures.

Earth plaster mortars are made of a pre-mixed plaster blend or sieved earth mixed with water. Earth extracted from the ground is composed of clay, silt, sand and coarse particles and sieving serves to remove the coarse particles, leaving the remaining finer aggregates that are compatible with plaster thicknesses. When the clay fraction is comparatively high, supplementary sand may be added to lean the mixture. The characteristics of earth mortars depends strongly on the type and content of the clay in contains (Lima et al., 2020).

Faria (2004) explains that calcium hydroxide ($Ca(OH)_2$), the main constituents of air lime, forms covalent bonds with the hydroxyls (OH) of the clays, promoting bonding. As clay retains water by ionic bonds, the presence of lime in a mortar hinders the retention of water in the clay by occupying the clay electrons.

In addition, as an earth mortar stabilised with lime dries, carbonation of the lime occurs in which it incorporates CO_2 present in the air and returns to its initial chemical configuration. Depending on the content of the air lime, this process consolidates the mortar to a rigid and porous structure, making it more resistant to the action of water while also maintaining the permeability of the plaster, allowing the masonry to release and absorb moisture without deteriorating the substrate (Santos et al., 2017).

However, as the production of lime requires the calcination of limestone in high temperature kilns (900°C), it is a significant producer of pollutants and emissions (Cunha, 2015).

In Brazil and many other regions of the world (Bamogo et al., 2020), cow dung is a further means of stabilising earth constructions from pavements to renders and has a vernacular tradition. This building technology is used and recognised by local populations to the present day and its use is transmitted orally (Pachamama, 2018).

Recent research (Millogo et al., 2016, Bamogo et al., 2020) has clarified that cow dung is rich in nitrogen, phosphorus, phosphoric acid and potassium. When added to earth mortars, these components react with kaolin and quartz present in the clay and produce insoluble silicate amines.

These compounds consolidate the constituents of the earth mixture and afford a measure of water resistance and hardness. In addition, the fibres present in the cow dung also hinder drying shrinkage and the formation of cracks, contributing to increased mechanical strength and adhesion.

In the Brazilian context, and in countries with a culture of cattle farming, cow dung may be a suitable option for the stabilisation of earth mortars, whether in traditional communities or in commercial works.

01 Cow dung “cured”, dry and seived

Cattle farming arrived during the colonial period and generates a large volume of cow dung daily. If improperly disposed of, this has a high potential for water contamination, as detiled by the Food and Agriculture Organisation of the United Nations (FAO, 2006).

In this sense, cow dung is an abundant residual material that has compatible structural qualities for stabilising earth mortars and can consequently be a more eco-efficient alternative to the use of air lime.

The objective of this research is, therefore, to evaluate the physical and mechanical properties of earth mortars produced with kaolinitic clays using two materials as stabilisers to compare the difference in the effects caused.

To assess the physical and mechanical properties of the earth mortars, tests and parameters were used that are specified in the German standard DIN 18947 (DIN, 2018) specifically for earth plasters. This standard refers in turn to several parts of the EN 1015 (CEN, 1999).

Materials and methods

Materials

For the composition of the mortars, a kaolinitic clay earth (KCE) sourced from the rural area near Itabirito

2: Preliminary shrinkage test with different sand proportions (KCE:sand ratio)

Table 1 Mortar designations, composition in mass, including water necessary to achieve 175 mm flow table consistency, and wet density

	Mortar sample	Earth:Sand		Stabiliser added		Water added	Mortar Fresh State Density
		Earth (%)	Sand (%)	Hydrated Lime (%)	Cow Dung (%)	(%)	(g/cm^3)
KCE:Sand (1:4)	**KCE-REF**	20	80	0	0	15	1.88
	KCE-5CL	20	80	5	0	16	1.81
	KCE-5CL+10CD	20	80	5	10	24	1.74
	KCE-10CD	20	80	0	10	24	1.59
	KCE-20CD	20	80	0	20	30	1.47

in the state of Minas Gerais, Brazil was chosen. The earth was sieved in the field with a coarse mesh (mesh aperture 2.79 mm). After air drying, the sieved earth was taken to the laboratory where it was sieved again according to the requirement of each stage of soil mineralogical and granulometric characterisation.

A washed sand of medium granulometry was used, with a grain diameter between 0.2 mm and 0.6 mm. The sand is siliceous, predominantly composed of quartz (SiO_2).

For this research a calcitic hydrated air lime, labelled CL, was used. In Brazil, limes for construction purposes are classified according to different levels of purity, and this lime is classified as CH-I (ABNT, 2003). According to the manufacturer (ICAL), this lime formulation does not contain unhydrated oxides in its composition. Due to its high concentration of calcium and magnesium hydroxides, CH-I hydrated lime has a high binding capacity and low water retention capacity.

The cow dung used, labelled CD, was also sourced from the rural area of Itabirito, Minas Gerais. The cows graze on pastureland, and therefore had enough plant fibres in their excrement.

Traditionally in the region, residents collect the fresh excrement in the cattle pen and pile it in the shade to "cure" it. In this process, heat, water, methane, carbon dioxide and ammonia are released (Bamogo et al., 2013). The excrement is turned daily for two weeks to aerate and cool the pile until, after 2 to 3 weeks, a dry material remains with only a mild odor and few lumps.

According to Millogo et al. (2016), when fresh, the cow dung contains 80 to 90% water in mass. After drying, the main components are vegetable fibres (essentially composed of cellulose, hemicelluloses and lignin) and organic amine compounds (from the evaporation of ammonia during drying in the shade). In addition, there is potassium, phosphoric acid and traces of quartz and clay ingested by the animal accidentally along with the grass.

In the laboratory, the cow dung was manually broken down and passed through a 2.79 mm sieve to remove any remaining thin branches, leaves and animal hair. The resulting material after sieving is very homogeneous and contains ample vegetable fibres whose length does not exceed 2 cm (Figure 1).

The mineralogical characterisation of the earth was performed with an X-ray diffractometer (XRD) for powder samples (Philips/PANalytical X'Pert Pro-APD with PW 3710/31 controller, PW 1830/40 generator and PW 3020/00 goniometer). A semi-quantitative chemical analysis was also performed using a sequential X-ray fluorescence (XRF) spectrometer (Philips/PANalytical PW-2400).

The particle size distribution of KCE was analysed by dry sieving and sedimentation, according to the EN 1015-1 (CEN, 1998a) and NBR 7181 (ABNT, 2016b) standards. A particle size distribuition test was not undertaken for the sand as it was already specified by the manufacturer on the packaging (PURA SÍLICA).

The liquid limit, plasticity index and hygroscopic humidity of the kaolinitic earth was also determined according to the NBR 6459 (ABNT, 2017) and NBR 7180 (ABNT, 2016a) standards.


03 Prismatic samples and plaster samples on adobe and brick in the laboratory

Mortars and samples

To achieve the objective of this work, five mortars were formulated. One of which is a reference mortar and the other four have the following additions: 5% of air lime, labelled KCE-5CL; 10% of cow dung, labelled KCE-10CD; 20% of cow dung, labelled KCE-20CD; and a blend of 5% air lime with 10% of cow dung, labelled KCE-5CL+10CD.

To define the mortar formulations and the necessary addition of sand to produce mortars with limited shrinkage, a preliminary shrinkage test was performed by observing crack occurrence on the surface of a plastered masonry block (Figure 2).

The preliminary shrinkage test showed that is necessary to add 4 parts of sand to 1 of earth. Consequently, all five subsequent mortar formulations have the same 1:4 proportion of KCE:Sand in their composition (Table 1).

The mortars were produced using an electrical mechanical mixer according to the instructions given in DIN 18947 (DIN, 2018), and the fresh mortars were characterised by the flow table consistency using the test procedures described in EN 1015-3 (CEN, 1999a), and the wet density, according to EN 1015-6 (CEN, 1998b).

A different stabilising material and a different quantity of water was added to each mortar formulation to obtain a 175 mm flow table consistency (DIN, 2018). In addition, all fresh mortars had a density > 1.2 kg/dm^3 (Table 1), as required by the DIN standard.

To perform the tests, two types of samples were produced with each formulated mortar: four 16 × 4 × 4 cm prismatic samples for linear shrinkage, dry density, flexural and compressive strength tests, and two samples of plaster on a substrate for the adhesion test, one on adobe and one on ceramic brick, so that the influence of the substrate could be assessed. All were plastered on ther largest face (30 × 20 cm) to a thickness of 1.5 cm.

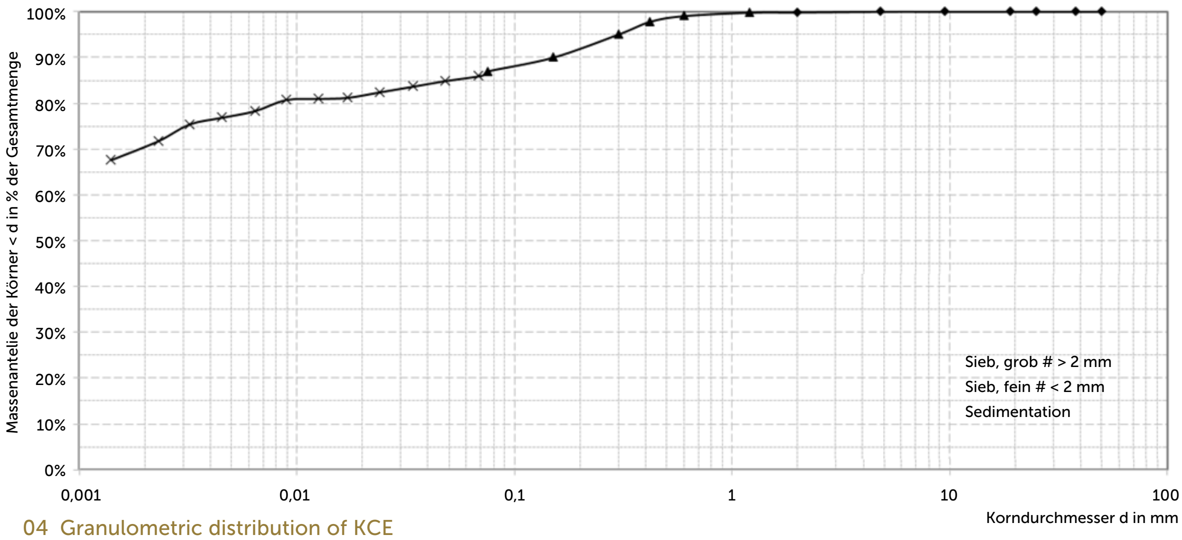
The samples were produced and stored in the laboratory at 63% relative humidity (RH) and 26°C (Figure 3) and remained in the laboratory environment from their production until the tests were carried out. All samples were tested between the ages of 50 and 60 days, after reaching a constant mass and to provide time enough for the hydrated lime carbonation process.

Mortar test methods

To assess linear drying shrinkage, three prismatic samples were used according to the guidelines of standard DIN 18947 (DIN, 2018). The same three prismatic samples were used to assess the dry bulk density according to EN 1015-10 (CEN, 1999b).

The adhesive strength of the samples of plasters on the adobe and ceramic brick blocks according to EN 1015-12 (CEN, 2000). To perform the test, a DYNA Z16 Pull-off Tester (PROCEQ) and a structural adhesive based on epoxy resin were used.

To determine the flexural and compressive strength, the EN 1015-11 (CEN, 1999c) standard was followed. Firstly, the flexural test was performed, breaking



04 Granulometric distribution of KCE

3 samples per formulation. Then, the axial compression test was performed on the resulting six halves. For both tests, a Shimadzu Universal Testing Machine (model AGS-X 300 kN) was used.

For the flexural test, a 5 kN load cell was coupled and configured at a constant speed of 0.2 mm/min on a vertical load application. For the compression test, the 5 kN load cell was maintained and the speed was set to 0.7 mm/min.

Results and discussion

Material characterisation

The results of the mineralogical characterisation are shown in Table 2. One can see an abundance of Kaolinite $Al_2Si_2O_5(OH)_4$, followed by Quartz SiO_2 in the KCE sample, followed by a lower proportion of Goethite: $FeO(OH)$, Moscovite: $KAl_2Si_3AlO_{10}(OH)_2$ and Microcline: $KAlSi_3O_8$.

Table 2 Mineralogical characterisation of KCE

Kaolinitic Clay Earth
XRF (Am20-020) – elements present:
Al, Si, Fe, O (high)
Ti, Mn, Cr, P (low)
K, S, Mg, Cl, Ni, Zr, Cu (traces)
XRD (Am19-4220) – minerals (phases) present:
Kaolinite (abundant)
Quartz (abundant)
Muscovite (low)
Microcline (low)
Goethite (low)
Rutile (trace)

The particle size distribution is shown in Figure 4. The granulometric characterisation results reveals a composition of 70% clay fraction, 15% sand fraction and 15% silt fraction.

These results also make it possible to affirm that after adding four parts of sand to one part of KCE earth, the final granulometric composition of all five mortar formulations is 14% kaolinitic clay, 3% silt and 83% sand. In addition, a percentage of water and stabilising additives are also added.

It was also determined that KCE has liquidity limit LL = 54%, the plasticity index PI = 23% and a hygroscopic humidity of 14%. The density of the KCE is d = 1.06 g/cm^3, the medium sand density is d = 1.38 g/cm^3, the CH-l density is d = 0.56 g/cm^3, and the cow dung CD density is d = 0.38 g/cm^2.

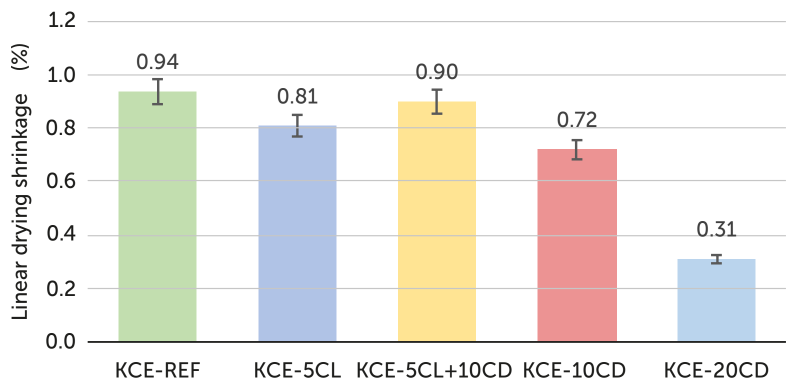
Flow table and wet density

To achieve a flow table consistency of 175 cm, it was generally necessary to add water when adding stabilisers. With the addition of stabilisers, the wet density decreases (Table 1).

Linear drying shrinkage

On the linear shrinkage test, all mortars comply with the requirements given in DIN 18947 (DIN, 2018) and exhibit a shrinkage index < 2% (Figure 5).

One can also see that the addition of cow dung alone appears to be more efficient at reducing the shrinkage of the earth mortar than the addition of air lime together with cow dung.



05 Linear drying shrinkage of kaolinitic earth mortars with the addition of air lime (CL) and cow dung (CD): average and standard deviation

Apparent dry bulk density

The dry bulk densities of all mortars exhibit classifiable values with respect to the parameters given in DIN 18947 (DIN, 2018) (Figure 6). The reference mortar KCE-REF and the mortar with 5% of air lime (KCE-5CL) have a bulk density class of 1.6; the mortars with both lime and cow dung (KCE-5CL+10CD) of 1.4; the mortars with 10% and 20% cow dung (KCE-10CD and KCE-20CD) of 1.2 and 1.0 respectively.

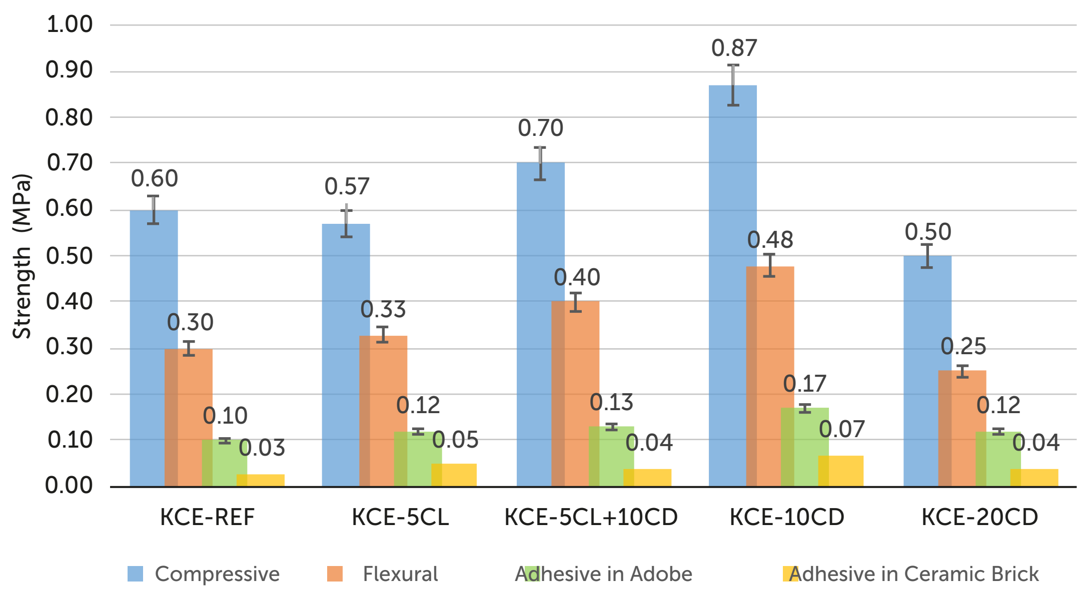
Flexural, compressive and adhesive strength

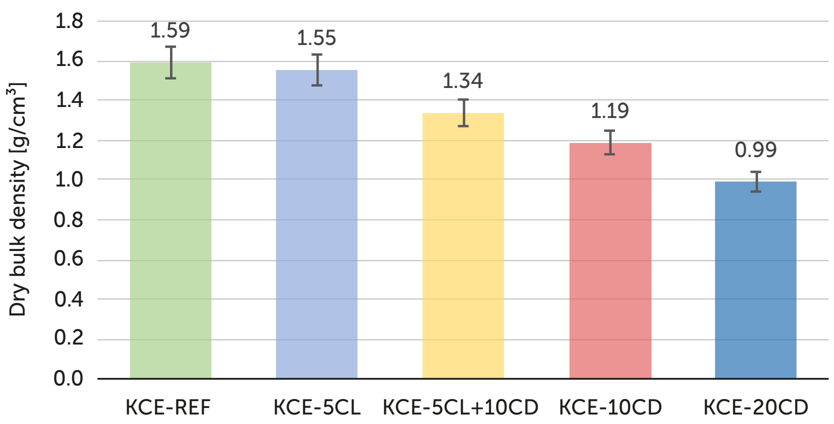
The results of the mechanical strength tests (Figure 7) show that the reference mortar (KCE-REF) without stablisers has the minimum flexural strength (Fs) value classifiable by DIN standard, Fs = 0.3 MPa. The addition of lime increases the Fs by 10% and the addition of 10% cow dung increases it by 60%. The simultaneous addition of both additives resulted in a 33% increase while the addition of 20% cow dung reduced the flexural strength of the reference mortar by 17%.

In terms of compressive strength (Cs) test, none of the mortars reached Cs = 1.0 MPa and therefore none are classifiable according to the DIN standard. However, all mortars could be classified as general plastering mortars as per EN 998-1 (CEN, 2016) because they all meet the minimum limit of 0.4 MPa. According to Röhlen and Ziegert (2011), earth mortars generally exhibit values for compressive strength between 0.6 and 3 MPa. Only the mortar with 20% cow dung exhibited a lower value.

The reference mortar exhibited a Cs = 0.6 MPa. The addition of 5% hydrated air lime reduce the compressive strength by 5% but the addition of 10% cow dung,

07 Compressive, flexural and adhesive strengths on adobe and brick of earthen mortars with air lime (CL) and cow dung (CD) additions: average and standard deviation





06 Dry bulk density of earth mortars with air lime (CL) and cow dung (CD) additions: average and standard deviation

increased it by 45%. The combined addition of lime and cow dung increased Cs by 17% and the addition of 20% cow dung reduced it by 17%.

The adhesve strength (As) was tested on two substrates: adobe and ceramic brick. On ceramic bricks, only KCE-5CL and KCE-10CD achieved the minimum value of As = 0.05 MPa specified in the DIN (2018). In relation to KCE-REF (As = 0.03 MPa), KCE-5CL increased the adhesive strength by 67% and KCE-10CD increased it by 133%.

The earth mortar formulations applied on the adobe block all conformed to the classifiable values given in the DIN (2018). In relation to KCE-REF (As = 0.10 MPa), KCE-10CD increase the adhesive strength by 70%, while KCE-5CL and KCE-20CD increased it by 20%, and KCE-5CL+10CD by 30%.

The results show that the addition of 5% air lime slightly reduces the compressive strength in relation to the reference mortar KCE-REF, but slightly increases the flexural and adhesive strength on both substrates. As observed in Gomes et al. (2018) for another kaolinitic earth, this occurs because the weak structural matrix created by the calcium carbonate compromises the connections between the clay sheets, damaging the clay's structural matrix. But because the proportion of lime added is low (5%), the lime does not form a strong enough structural matrix, resulting in an overall reduction in the compressive strength of the mortar.

Faria (2018), however, has shown in tests that earth mortars with more than 20% of air lime can increase the mechanical strength of mortars.

The results also show that in comparison to the addition of 5% lime, the addition of 10% cow dung and the combined addition (KCE-5CL+10CD) exhibits superior performance in all the evaluated tests.

According to Bamogo et al. (2020) the vegetable fibres present in the cow dung and the insoluble silicate amines formed are responsible for the effects seen in the earth mortar formulations with this additive. The researchers suggest that the insoluble silicate amines ($Si(OH)_4NH_3$) are formed in the reaction of the ammonia compounds present in cow dung with the fine quartz (SiO_2) and kaolinite ($Al_2Si_2O_5(OH)_4$) present in the soil.

Bamogo et al. (2020) investigated the addition of 2, 4 and 6% by weight of cow dung to the earth mortar mixtures and showed that the positive effects caused increase with the proportion of cow dung added.

Vilane (2010) evaluated the addition of greater proportions of cow dung – 5, 10, 15 and 20% – to the earth mass for producing earth blocks (adobe). The results indicated the addition of 10% cow dung produced the best performance in relation to mechanical strength and water absorption. The results of our research would seem to corroborate Vilane's findings: the volumetric addition of 10% cow dung had a more advantageous effect on the KCE earth mortars than 20%.

On the other hand, the simultaneous addition of 10% cow dung and 5% lime improved the performance of the reference mortar in all tests but was not as effective as adding each of the same additions separately.

It is interesting to observe that the shrinkage of KCE mortars correlates directly to the performance of the mechanical strength and adhesion of mortars. Although not visible to the human eye, the mortar with the lowest shrinkage should produce fewer microcracks in the plaster and offer an improved contact surface and, therefore, better adhesion to the substrate, as well as greater mechanical resistance.

Conclusions

The kaolinitic reference mortar, without any stabilising additions, is a mortar that presents satisfactory performance in all tests. The addition of the tested stabilising substances did provide some improvements.

The addition of 5% of air lime reduced linear shrinkage by 14%, reduced compressive strength by 5%, increased flexural strength by 10% and increased adhesive strength on an adobe substrate by 20%.

The addition of 10% of cow dung, exceeded the results of adding lime in all tests, and offers proof of the quality of the traditional vernacular method of stabilising earth mortars. In fact, the mortar with 10% cow dung increased compressive strength by 45%, flexural strength by 60% and adhesive strength by 133%, making it a very efficient addition to earth plasters. This mortar exhibited better characteristics than the mortar with both air lime and cow dung.

The effect of adding cow dung as a stabiliser to earth mortars has also been evaluated by other researchers. Those investigations also conclude that the addition of cow dung reduces shrinkage and increases mechanical strength. However, no other existing research was found that compared the effects of adding cow dung with the addition of lime, or the effect of adding a blend of air lime and cow dung to the same base earth mortar. This allows us to get a sense of the performance of these additivies compared to other stabilising binders already documented in the literature.

The investigation presented here contributes to the field of research into the uses of cow dung in construction and shows that it offers great potential for the stabilisation of earth mortars. Future research will analyse the effect of these stabilisers on the durability of earth mortars.

Acknowledgements

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