USING ALGINATE BIOPOLYMER TO ENHANCE THE MECHANICAL PROPERTIES OF EARTH-BASED MATERIALS

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Abstract

Natural materials such as sugars or biopolymers are commonly used to stabilize and enhance the mechanical properties of earth-based building materials. Among them, brown seaweed polymers such as alginate have been recently used to improve the design of earth building materials. With its molecular structure, alginate can form a strong network with clay particles that strengthens the material. We here focus on the mix-design of earth based materials using a model earth-based material based on a mix of sand and kaolinite and a real raw earth material. We have worked on castable earth-based material. The fluidity of the castable earth has been reached by using s dispersant (hewapetaphosphate) to reduce the apparent yield stress of the material. The gelification of the alginate has been advantageously used to shorten the demoulding time. The effect of alginate on the compressive strength has been shown to depend on its dosage ad on the mineralogy of the soil. If alginate increases the strength of kaolinite-based samples, it does not influence the behavior of earth-based materials with swelling particles. We finally study the possibility to reinforce earth-based materials containing alginate with flax fibers.

Keywords:

Earth-based materials, alginate, flax fiber

1 INTRODUCTION

Earthen construction has recently regained much attention in the building industry due to its low environmental impact and recyclability (Azeredo et al. 2008; Bui et al. 2009; Aubert et al. 2015; Moevus et al. 2015). The development of earthen construction is still limited because of the time required by the material to harden and by the difficulty to achieve a mix-design that allows for both fast casting and sufficient strength in the dry state. In order to answer both problems and to improve mix-design of earth-based materials, a recent trend has been to apply scientific knowledge and expertise, developed by the concrete industry, to earthen construction (Gnanli et al. 2014; Moevus et al. 2015; Ouellet-Plamondon and Habert 2016).

One of the options adopted from concrete technology is the optimization of the granular skeleton (Moevus et al. 2015) which increases the dry density of earth material and thus its mechanical strength. Another option is to use a coagulant or a hydraulic binder in order to shorten the material's hardening stage (Walker and Stace 1997; Venkatarama Reddy and Prasanna Kumar 2011a; Venkatarama Reddy and Prasanna Kumar 2011b; Khelifi et al. 2013; Tripura and Singh 2014; Gnanli et al. 2014; Khelifi et al. 2015; Miccoli et al. 2015). This last option, emanating from concrete mix design, is to improve the earth material's workability to enable the possibility of making an extrudable, flowable and even castable earth material (Gnanli et al. 2014; Moevus et al. 2015). For this last option, the objective is to deflocculate the micro-sized clay-based structures in order to reduce the interaction force between clay particles. The deflocculation can be obtained by using a dispersant which acts just like a superplasticizer on cement particles in concrete (Flatt 2004; Kjeldsen et al. 2006; Zingg et al. 2008; Roussel et al. 2010; Perrot et al. 2012; Perrot et al. 2016). This option is also expected to lead to a reduction of the material porosity and therefore improve material strength and durability (Moevus et al. 2015).

However when using casting for earth-based materials, we are facing the problematic of the strengthening time of the material: Contrary to cement or lime-based materials, no "fast" chemical reaction responsible for the material hardening occurs and we have to wait for the drying of the sample to obtain sufficient mechanical strength for sustaining its own weight.

One solution to this problem is to use a gelling agent to obtain what is called "green strength" for concrete to allow for a fast demolding of the earth-based material. Alginate seems to be a solution and is a family of seaweed biopolymers which are alginic salts obtained from the cell walls of brown seaweed. Alginate can form a cross-linked isotropic insoluble gel when a soluble form of alginate nucleates with divalent metal cations like Ca^{2+} which can be found in earth-based materials. Chains of alginate make junctions by intercalating divalent cations creating a sort of egg-box connection (Funami et al. 2009).

Alginate has already been studied as a binder for clays and even for earth-based materials for building applications (Achenza and Fenu 2006; Galán-Marín et al. 2010; Dove et al. 2016). In their studies, the authors show that depending on their chemical nature, alginate is able to increase the mechanical strength and abrasive resistance of the soils. However, some effects of the alginate of clay system remain unexplained and those studies do not study the potential of alginate to be used as a gelling agent for raw earth casting.

In this study, we use alginate in combination with a dispersant (hexametaphosphaste) as additives in earth-based materials in order to mix-design castable products. Two types of earths are tested (a kaolin-based mortar and a real raw earth) that are cast with vibration within rectangular mold. Finally, reinforcements by flax fibers are also tested. Our study focused on the mechanical strength of the samples and shows that the strengthening effect of alginate depends on the type of soils and on its dosage. We also study the effect of flax fibers on the mechanical behavior of alginate treated earth-based materials.

2 MATERIALS AND METHODS

The first tested materials is a kaolin mortar designed using Dreux and Gorisse mix-design method (Dreux and Festa 1998). The mix-design methodology is described in Menasria et al. work (Menasria et al. 2017).

The kaolin clay used was provided by Imerys and came from the “Kaolins de Bretagne” quarry at Ploemeur, France. The kaolin clay had a specific gravity of 2.65 and a specific surface area 10 m²/g. The largest clay grain size was approximately 10 μm and the mean kaolin grain size approximately 4 μm. The particle size was measured in ethanol using a laser particle size analyzer and is set out in figure 1. The paste used in the tests consisted of a mixture of kaolin clay powder and water.

The clay is mixed with two different sands: a fine one, with grain size ranging from 63 to 200 μm, and a coarser one with grain size ranging from 0 to 4 mm. The grain size distributions of the sands are also plotted in figure 1.

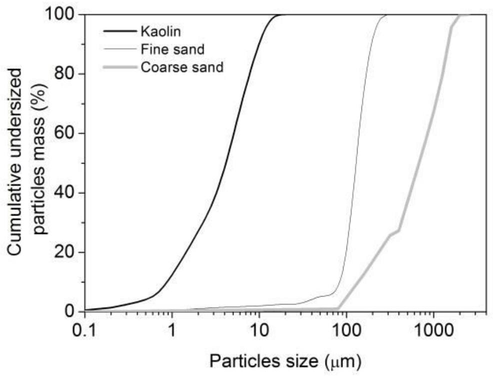

Fig. 1: Particles size distribution of the powders

The final PSD of the ternary mix of powder optimized using Dreux and Gorisse method (Dreux and Festa 1998) is plotted in figure 2. This composition allows for the best mechanical strength with this ternary mix (Menasria et al. 2017). It is composed in mass (and volume, as all particles have almost the same density) of 17% kaolin, 23% fine sand and 60% coarse sand. We can observe a plateau on the PSD between 10 and 60 μm, because neither the kaolin nor sand have those particle sizes.

The second tested material is a raw earth coming from Saint-Sulpice-La-Forêt (Ille et Vilaine, France). It is a fine soil with a PSD showing 70% particles finer than 10 μm (the PSD is plotted of figure 2). The clay particles are a mix of quartz, kaolinite, illite and smectite as shown by XRD analysis before and after thermolysis at 550°C (Figure 3). The Plasticity index of this soil is 21 with a liquid limit of 48% and a plastic limit of 27% for the water content.

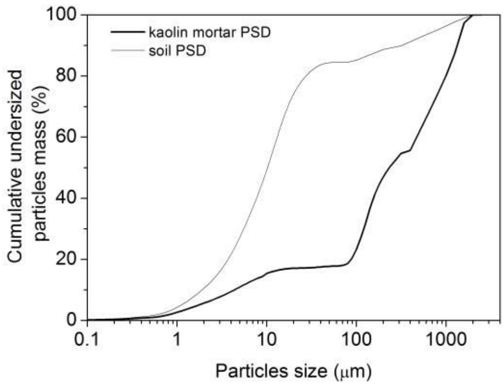

Fig. 2: Particles size distribution of the kaolin mortar and Saint-Sulpice-La-Forêt soil

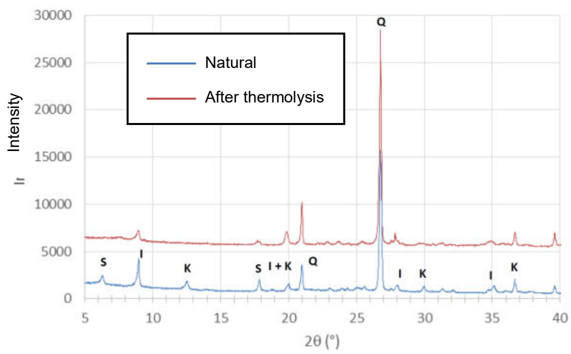

Fig. 3: XRD Analysis of the soil from Saint-Suplice-La-Forêt : natural and after thermolysis.

The used alginate is a white powder of alginic salt Cimalgin HS3® provided by Cimaprem (Redon, France). It is designed to make high strength gel for arts and molding applications. Dosages ranging from 1 to 5% are tested within the field of this study.

Hexametaphosphate (HMP) is used as a dispersant in this study to make the mortar flowable. For the kaolin mortar, dosages of 0.25 % of the kaolin clay content is tested based on previously obtained results on the effect of dispersant on the rheological behavior of clay pastes (Perrot et al. 2016). For the soil from Saint-Sulpice-La-Forêt, the mass ratio of HMP is 0.3% of the dry material. The choice of this dosage was made using the same methodology than the one used for the kaolin mortar in (Perrot et al. 2016).

The dispersed flax fibers (Marylin variety) used in this study was supplied by the CTLN® Company (Le Neubourg, France). The fibers, shown on Figure 4, were scutched, carded and cut into 4 mm lengths. These flax fibers were the same as those used in the study by Bourmaud et al. (Bourmaud et al. 2013). The volume fraction of fibers is fixed at 4% in the present study.

Fig. 4: Dispersed flax fibers and woven fabric of flax fibers.

Samples are cast in three layers within rectangular parallelepiped molds (40x40x160 mm^3). A vibration period of 60 seconds is performed after each layer casting. Layer surface is then scratched to avoid the formation of cold joints.

Samples are then conserved in a 40°C temperature controlled storage until weight stabilization. Once the mass reaches its final value, the flexural (3 points test) and compressive strength of the sample is measured using a 50 kN loading frame. The test is carried out at a constant velocity of 1 mm/min.

3 COMPRESSIVE STRENGTH OF THE SAMPLES

The compressive strengths of the samples are measured once the samples are dry to provide a reference state for testing. The results are plotted on Figure 5 for the kaolin mortar and in Figure 6 for the soil from Saint-Sulpice-La-Forêt.

For kaolin mortar, the addition of alginate at dosage of 1% does not change the mechanical strength of the sample. In this case, the amount of alginate may be not sufficient to build a gel network able to reinforce the material. However, for higher dosage, the compressive strength of the sample increases with the alginate dosage. For a dosage of 3%, at a dry density of 2050 kg/m^3, the addition of alginate more than doubles the compressive strength (from 2.25 MPa to 5.9 MPa). At a dosage of 5%, the compressive strength reaches its maximal value of 7.1 MPa.

For the soil from Saint-Sulpice-La-Forêt, the addition of alginate does not change the compressive strength of the samples. Figure 6 shows that the compressive strength of the samples is not influenced by the addition of alginate in the range of tested dosage (from 0 to 4%). It can be here assumed that the level of the material without alginate is stronger (or at least of equal strength) than the alginate gel network. Therefore, the addition of alginate does not modify the mechanical strength of the samples as it does not reinforce the soils particles network that highlights stronger interactions, maybe due to the presence of swelling clays like smectite at a dry state (high suction effect).

By comparing the effect of alginate addition on the compressive strength of both materials, it can be concluded that the ability of alginate to strengthen an earth-based materials depends on its dosage and on the mineralogy of the clay particles in the soil. Figure 7 summarized the effect of alginate on both tested materials regarding its dosage.

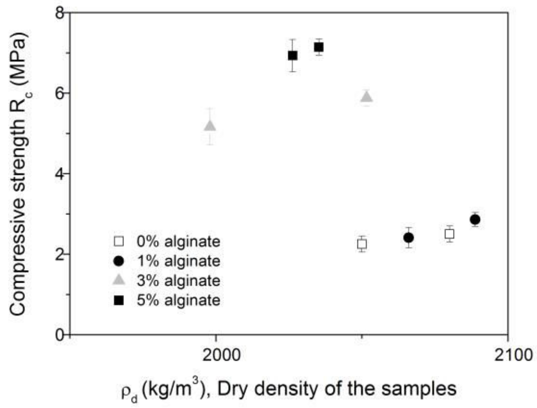

Fig. 5: Compressive strengths of cast kaolin mortar samples with alginate content (mass fraction of the kaolin powder) ranging from 0 to 5% vs dry density.

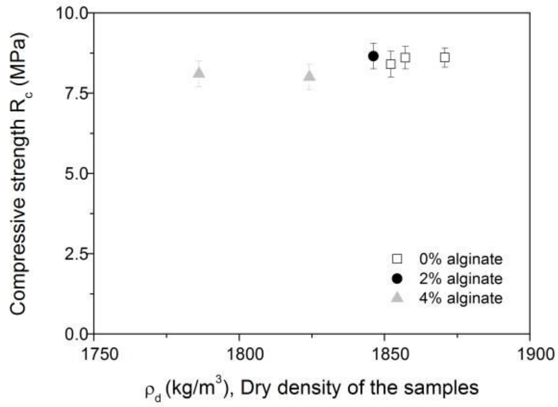

Fig. 6: Compressive strengths of cast soil (Saint-Sulpice-La-Forêt) mortar samples with alginate content (mass fraction of the soil) ranging from 0 to 4% vs dry density.

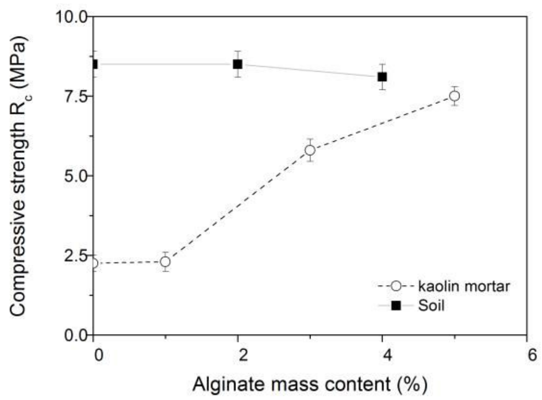

Fig. 7: Evolution of compressive strength of tested materials with alginate dosage at a fixed dry density (extrapolated value at 2050 kg/m^3 for the kaolin mortar and 1850 kg/m^3 for the soil from Saint-Sulpice-La-Forêt).

For kaolin earth-based material, the addition of a sufficient amount of alginate is able to strengthen the material (up to three times the compressive strength of the sample without any alginate). On the other side, for the soil from Saint-Sulpice-La-Forêt that contains swelling clay (smectite), alginate does not increase the compressive strength of the material, even at high dosage. The gel strength seems to be weaker than the interaction within clay particles network.

4 FLAX FIBER REINFORCEMENT

In this part we only focus on the kaolin mortar because it is for this kind of material that addition of alginate is the most advantageous.

In Figure 8 is plotted the evolution of the compressive strength of the kaolin mortar sample with regard to the dry density. Firstly, it can be observed that the addition of flax fibers induces a decrease of the density of the sample. This can be attributed to both phenomena: a workability decrease due to the fibers (leading to higher void content) and to the low specific density of the fibers. Secondly, the mechanical strength of the samples only increases with the addition of fibers for an alginate dosage of 1%. It appears that for higher dosage, fibers do not increase the compressive strength of the samples because the cohesion of the material is higher than the strength of the interface between fiber and mineral matrix as shown in Menasria et al. (Menasria et al. 2017). For dosages of 3 and 5% of alginate, the addition of fibers seems to have no effect as the measured mechanical strengths of samples with and without fiber seems to be on the same line on Figure 8 with respect to the dry density.

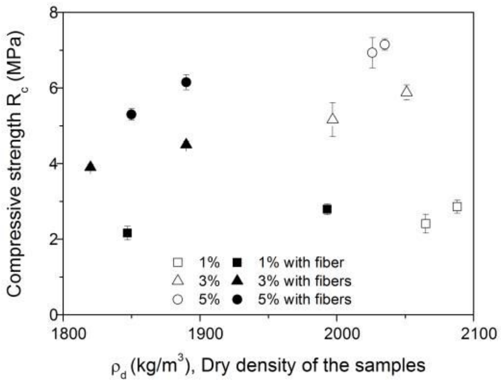

Fig. 8: Evolution of compressive strength of samples of kaolin mortar with dry density for different dosages or alginate (1, 3 and 5%) with and without flax fibers.

One beneficial aspect brought by the fibers is the increase of the ductility of the material. In Figure 9 force versus displacement curves obtained during the compressive strength measurements with and without fibers for alginate dosages of 3 and 5% are plotted. If we compare curves for samples with and without fibers, we can see that the elastic parts of the curve before the peak are close meaning that fibers addition does not influence significantly the elastic modulus. The peak is higher for samples without fibers, as confirmed by Figure 8, however, after the load peak; the load decrease is much slower for samples with fibers. Such type of behaviour traduces an increase in the ductility of the sample and is very interesting for use in seismic area.

Figure 10 shows the evolution of flexural strength of the samples of the kaolin mortar with dry density for different dosages of alginate (1, 3 and 5%) with and without fibers. The results are close to the one obtained for compressive strength. Once again, the beneficial effect of fibers on the strength is obtained only for the lowest alginate dosage for which the mineral matrix is the weakest. For higher dosages of alginate, effect of fibers is not so obvious but the flexural strength remains constant even if the dry density decreases with the addition of fibers.

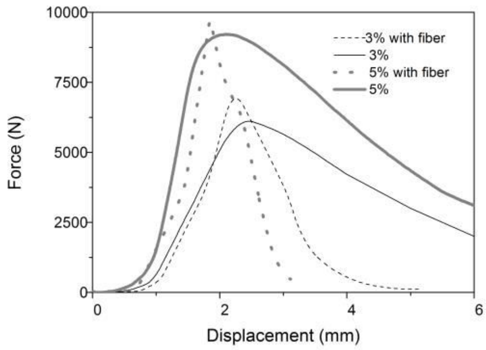

Fig. 9: Force versus displacement curved obtained during the compressive strength measurements on kaolin mortar with and without fiber for alginate dosages of 3 and 5%.

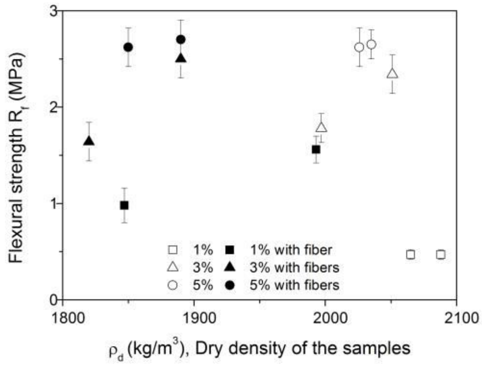

Fig. 10: Evolution of compressive strength of samples of kaolin mortar with dry density for different dosages or alginate (1, 3 and 5%) with and without flax fibers.

Figure 11 shows the force versus displacement curves measured during the flexural strength tests.

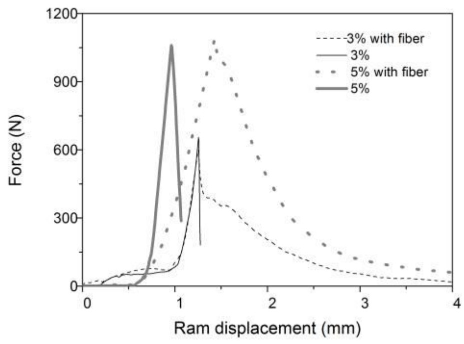

Fig. 11: Force versus displacement curved obtained during the compressive strength measurements on kaolin mortar with and without fiber for alginate dosages of 3 and 5%.

We can see that samples without fiber exhibit a brittle behaviour with a sudden failure obtained after the load peak whereas the samples with fibers shows a post-peak behaviour with a smooth decrease of the load due to the continuous breakage of the interfaces between fibers and matrix (Khelifi et al. 2015).

5 CONCLUSIONS

In this paper we have investigated the potential use of alginate to be used as a reinforcing agent for earth-based materials. We have shown that for kaolin clay based materials, this kind of seaweed biopolymer when added in sufficient amount is able to strongly increase the strength of the material (up to 3 times the compressive strength without alginate). On the other hand, we have also observed that when the interaction between clay particles are strong (i.e. within a dry material containing swelling clay), the alginate gel is too weak to improve the mechanical behavior of the material.

Finally we have studied the effect of flax fibers reinforcement on the mechanical behavior of alginate treated kaolin based mortar. We have observed that fibers addition decreases the specific density of the samples but only improves the strength of the samples at the lowest dosage of alginate. However, flax fibers have a significant effect on the ductility of the material.

6 AKNOWLEDGMENTS

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7 REFERENCES

Achenza M, Fenu L (2006) On Earth Stabilization with Natural Polymers for Earth Masonry Construction. Mater Struct 39:21–27.

Aubert JE, Maillard P, Morel JC, Al Rafii M (2015) Towards a simple compressive strength test for earth bricks? Mater Struct 1–14.

Azeredo G, Morel J-C, Lamarque C-H (2008) Applicability of rheometers to characterizing earth mortar behavior. Part I: experimental device and validation. Mater Struct 41:1465–1472.

Bourmaud A, Morvan C, Bouali A, et al (2013) Relationships between micro-fibrillar angle, mechanical properties and biochemical composition of flax fibers. Ind Crops Prod 44:343–351.

Bui Q-B, Morel J-C, Hans S, Meunier N (2009) Compression behaviour of non-industrial materials in civil engineering by three scale experiments: the case of rammed earth. Mater Struct 42:1101–1116.

Dove CA, Bradley FF, Patwardhan SV (2016) Seaweed biopolymers as additives for unfired clay bricks. Mater Struct 49:4463–4482.

Dreux G, Festa J (1998) Nouveau guide du béton et de ses constituants. Eyrolles

Flatt RJ (2004) Dispersion forces in cement suspensions. Cem Concr Res 34:399–408.

Funami T, Fang Y, Noda S, et al (2009) Rheological properties of sodium alginate in an aqueous system during gelation in relation to supermolecular structures and Ca 2+ binding. Food Hydrocoll 23:1746–1755.

Galán-Marín C, Rivera-Gómez C, Petric J (2010) Clay-based composite stabilized with natural polymer and fibre. Constr Build Mater 24:1462–1468.

Gnanli L, Ouellet-Plamandon C, Brumaud C, Habert G (2014) Development of a Self-Compacted Clay based Concrete, rheological, mechanical and environmental investigations. Barcelona, Spain,

Khelifi H, Lecompte T, Perrot A, Ausias G (2015) Mechanical enhancement of cement-stabilized soil by flax fibre reinforcement and extrusion processing. Mater Struct 1–14.

Khelifi H, Perrot A, Lecompte T, Ausias G (2013) Design of clay/cement mixtures for extruded building products. Mater Struct 46:999–1010.

Kjeldsen AM, Flatt RJ, Bergström L (2006) Relating the molecular structure of comb-type superplasticizers to the compression rheology of MgO suspensions. Cem Concr Res 36:1231–1239.

Menasria F, Perrot A, Rangeard D, Le Duigou A (2017) Mechanical enhancement of casted and compacted earth-based materials by sand, flax fiber and woven fabric of flax. Clermont-Ferrand, France,

Miccoli L, Oliveira D, Silva R, et al (2015) Static behaviour of rammed earth: experimental testing and finite element modelling. Mater Struct 48:3443–3456.

Moevus M, Jorand Y, Olagnon C, et al (2015) Earthen construction: an increase of the mechanical strength by optimizing the dispersion of the binder phase. Mater Struct 1–14.

Ouellet-Plamondon CM, Habert G (2016) Self-Compacted Clay based Concrete (SCCC): proof-of-concept. J Clean Prod 117:160–168.

Perrot A, Lecompte T, Khelifi H, et al (2012) Yield stress and bleeding of fresh cement pastes. Cem Concr Res 42:937–944.

Perrot A, Rangeard D, Levigneur A (2016) Linking rheological and geotechnical properties of kaolinite materials for earthen construction. Mater Struct 1–9.

Roussel N, Lemaître A, Flatt RJ, Coussot P (2010) Steady state flow of cement suspensions: A micromechanical state of the art. Cem Concr Res 40:77–84.

Tripura D, Singh K (2014) Behavior of cement-stabilized rammed earth circular column under axial loading. Mater Struct 1–12.

Venkatarama Reddy BV, Prasanna Kumar P (2011a) Cement stabilised rammed earth. Part A: compaction characteristics and physical properties of compacted cement stabilised soils. Mater Struct 44:681–693.

Venkatarama Reddy BV, Prasanna Kumar P (2011b) Cement stabilised rammed earth. Part B: compressive strength and stress–strain characteristics. Mater Struct 44:695–707.

Walker P, Stace T (1997) Properties of some cement stabilised compressed earth blocks and mortars. Mater Struct 30:545–551.

Zingg A, Holzer L, Kaech A, et al (2008) The microstructure of dispersed and non-dispersed fresh cement pastes — New insight by cryo-microscopy. Cem Concr Res 38:522–529.