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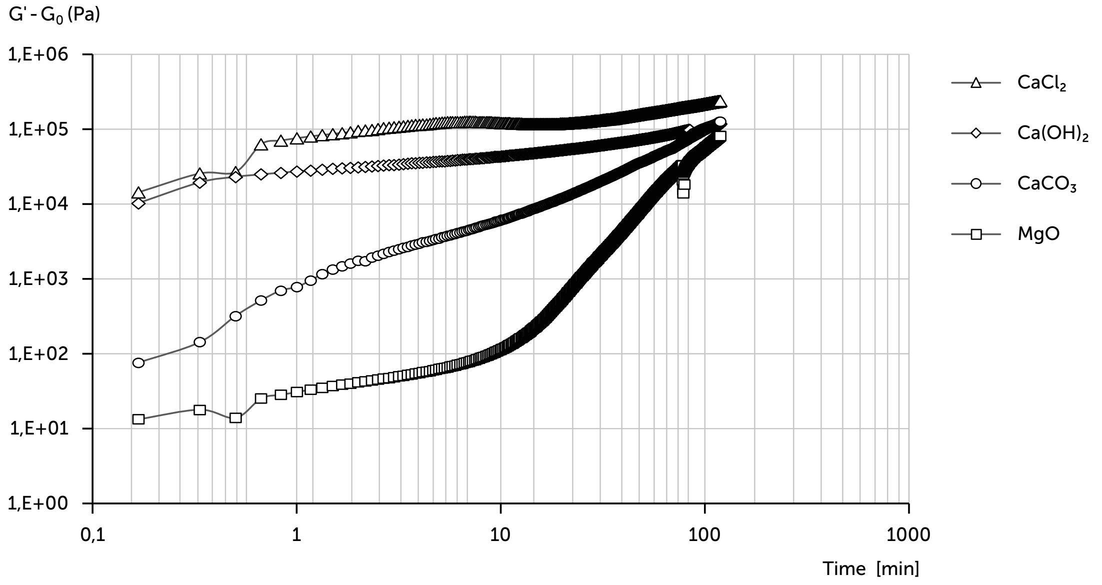
The slower it is, the stronger it will be: How to improve poured earth strength without stabilisation

Earth material is readily available, but widening its use into contemporary cities urges us to invent constructive technologies which could facilitate a quick use of excavated earth on site [1, 2]. This would drive the construction sector towards a closing material loops and engage the transition of the sector into circular economy [3]. Recent studies on earth construction techniques developed a new technology based on casting [2, 4] but with a much lower environmental impact. Considering that the rheological behaviour of clays is controlled by their surface charge, we first introduce potential determining ions to deflocculate the clay particles and to reduce the yield stress of the earth material. Their efficiency is characterised using zeta potential measurements and rheological tests. We then achieve the flocculation of clay particles by using natural minerals that slowly dissolve in the interstitial liquid and ultimately precipitate calcium silicate hydrate (C-S-H). The combination of concrete and ceramic technologies can transform earthen architecture and provide a material that is as easy and cheap to use as current concrete products. This approach is possible because clays share many similarities with cementitious materials in terms of colloidal interactions and adhesion forces [5], even if the cohesion forces between the particles are much weaker for clay particles than those of cement particles [6] due to the absence of hydraulic reaction.

Strategies have been investigated to develop poured earth without hydraulic binder. These different approaches all use clay dispersants such as sodium polyacrylate (NaPa), sodium silicate (NaSil) and sodium hexametaphosphate (NaHMP) [7–10] earth is usually not used for modern construction due to the expensive, artisanal and complicated process and the high variability of the raw material. The transfer of techniques dedicated to cement concrete could help the industrialisation of this material. The use of dispersant for an improved dispersion of the earth powder has been investigated for both dispersion of earth fine fraction and water (here named the binding phase to allow the material to flow with a limited amount of water. In addition, the use of a dispersant leads to an increase in the strength from 3 MPa to 5-6 MPa by changing the clay particle organisation, which results in an increase in the clay particle interaction [7-9]. The sample becomes denser, with less global porosity compared to the nonadjuvanted fluid sample, and consequently becoming stronger

To be able to unmold fluid earth without hydraulic binder, a strategy based on the deflocculation and flocculation of clay particles has been developed [4, 11]. This approach explores the deflocculation of a mix through the addition of phosphate or silicate-based inorganic dispersants and the delayed flocculation of the clay particles through the addition of calcium-based or magnesium-based additives. After the reaction between the dispersant and coagulant occurs, precipitate products are formed, annihilating the plasticizing effect of dispersant on the clay particles and allowing the material to set. It has been shown that additives react together, and consequently, clay platelet charges return to their initial state with an edge (+)/face (-) organisation.

To define how additives affect the material strength, this research will focus on their influence on the mortar properties at fresh and hardened states. Global air pores and water micropores will be established and compared after different resting times. One mineral dispersant (NaHMP) is used, and four mineral coagulants (magnesium oxide, MgO, calcium hydroxide, $Ca(OH)_2$, calcium carbonate, $CaCO_3$, and calcium chloride, $CaCl_2$) are chosen according to their water solubility, respectively +/- 0.001 mg/L, 0.15 mg/L, 1850 mg/L and 81300 mg/L. The clay and sand used



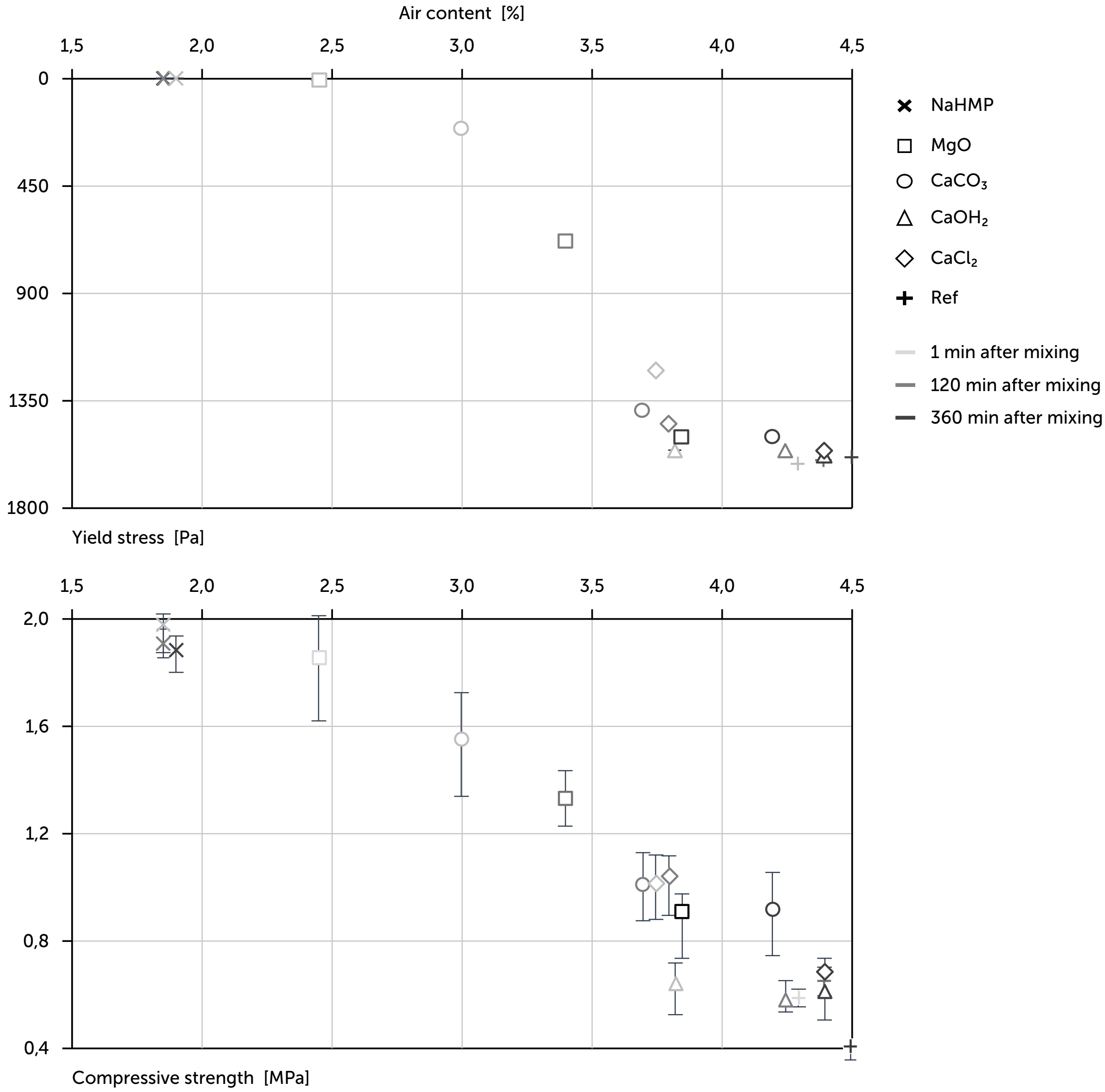
01 Variation in the storage modulus for kaolinite clay pastes prepared with 0.14% NaHMP and different coagulants with a molar ratio Mg/P or Ca/P equal to 1. The values are reported as a difference with respect to G_0, the modulus of the paste with NaHMP only.

in this study have known properties, the water-to-clay ratio (0.6) and the amount of NaHMP (0.14% by mass of clay, corresponding to the highest fluidity reachable before additive saturation) are kept constant to ensure that the observed behaviours are only due to the coagulants.

Results and discussion

In literature, it was reported that the base compound nature of coagulant has an influence on the structuration time of deflocculated clay paste [4, 12] but with a much lower environmental impact. Considering that the rheological behaviour of clays is controlled by their surface charge, we first introduce potential determining ions to deflocculate the clay particles and to reduce the yield stress of the earth material. Their efficiency is characterised using zeta potential measurements and rheological tests. We then achieve the flocculation of clay particles by using natural minerals that slowly dissolve in the interstitial liquid and ultimately precipitate calcium silicate hydrate (C-S-H). Viscoelastic measurements were carried out on the studied systems to highlight the impact of the type of coagulant on the time-dependent structural changes within the material. This testgives an indication of the strength of the particle network at a given time and provides information on the soft to rigid structure transition and the kinetics of the rigidification [13]. In Figure 1, for all tested clay pastes, an evolution in the storage modulus with time was observed, highlighting a change in the internal structure of the material. However, when considering each clay paste behavior in detail, for each coagulant compound introduced, the evolution is not similar. The coagulants do not present the same dissolution rate, explaining the observed differences. The different reaction kinetics, related to the type of coagulant used, seem to influence the structuration rate but not the type of structuration: all the clay pastes present the same behavior at the end of the reaction.

To evaluate the change in porosity in the samples over time and its influence on the compressive strength, the air content of each clay mortar at different times is measured (Fig. 2). This evolution of the air content according to the casting time induces different compressive strengths: the high amount of air measured in the reference clay mortar is associated to a low compression strength, and the low air content of the deflocculated clay mortars leads to a high compressive strength. In contrast, when coagulant is added to the deflocculated mixture, the air content evolves according to the resting time: they do not have the same results if they are tested and casted directly after mixing or after 120 min or 360 min. After 360 min, all the samples contain the same amount of air and, consequently, have a low compressive strength. Consequently, it can be suggested that the change in sample strength is linked to a change in porosity more than a change in the internal structure due to the precipitation products formed during the deflocculation/flocculation process. This observation sug-



02 Yield stress and compression strength as a function of the air content at different times of measurement for all clay mortars

gests that the state of structuration of the material at a given time governs the air content, which in turn affects the resistance by decreasing the density.

To validate this hypothesis on the microporosity, to study if clay platelet come back to their initial state or if minerals created during the process affect the earth, thermogravimetric analysis must be performed.

Conclusion

The compressive strength is highly sensitive to additives. Adding dispersant allows a substantial increase in strength. The macrostructure of the samples after deflocculation/flocculation process is different according to the water solubility of the used coagulant. The higher the water solubility of the coagulant is, the faster the reaction between the dispersant and coagulant will be, and the structural network at a given time will be different. This evolution of the yield stress, affecting the sample air content, will then impact the compressive strength. The dispersed sample will keep the highest compressive strength, and the coagulant used to quickly unmold the sample will automatically decrease its compression strength according to its solubility.

Further studies need to be done to confirm if coagulant does not impact the clay microstructure with the mineral precipitation product created during the reaction between the phosphate ions and calcium or magnesium ions. Based on literature, clay platelet might return to a face (-)/edge (+) house-of-cards organisation. In this case, only the porosity linked to air bubbles entrapped during the mixing phase has an influence on the final strength of deflocculated/flocculated samples.

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