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DEVELOPMENT OF A SELF-COMPACTED CLAY BASED CONCRETE - RHEOLOGICAL, MECHANICAL AND ENVIRONMENTAL INVESTIGATIONS

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Abstract
Without transport needs and infinite recycling possibilities, earth is one of the building materials with the lowest environmental impact, but its development is hindered by construction time with conventional earth construction technique. The objective of this study is to transfer technology from cement and concrete in earth construction in order to improve earth materials by providing a material that is as easy and cheap to use as current concrete products: a Self-Compacted Clay based Concrete (SCCC). This technology transfer can be done as both materials have analogies in terms of physics. Rheological and mechanical measurements performed in earth materials containing polymers and a cementitious binder show that it is possible to obtain a new earth material enough fluid to be poured in a formwork and getting a sufficient strength to be demoulded at early age. Furthermore, we show that its carbon footprint is competitive compared to the concrete block. As a conclusion, on one hand cement based construction is the mainstream construction technique but has a large environmental load. On the other hand, renowned architects are promoting earthen architecture but can't increase its use due to construction costs. This new building material can loosen current constraints and open new possibilities for a fast, cost efficient and sustainable earth construction.

Keywords:
earth; concrete; clay; environmental impact

1 INTRODUCTION

Traces of earthen architecture date back from 10'000 years ago and it still used in most climates and societies [Anger and Fontaine 2009]. Without transport and with infinite recycling possibilities, earth is one of the building materials with the lowest environmental impact [Morel 2007], [Shukla 2009] followed by a very efficient temperature and moisture regulation of indoor living spaces [Parra-Saldivar 2006]. We can currently observe a strong development of earth construction, probably due to environmental concern. However, this development is limited due to conventional earth construction technique (rammed earth, adobe, cob, etc…) time and cost consuming. On the other hand, we have cement, an incredibly easy material to use but that has a significant environmental impact [Schneider 2011]. In the latter material, a lot of engineering and science has been invested in order to improve the understanding and the processing of cement based concrete whilst in the case of earth no or very little engineering improvement has been made.

The objective of this study was then to transform earthen architecture by providing a material that is as easy and as cheap to use as current concrete products, by using cement and concrete new technologies. This technology transfer can be done as cement and clays have many analogies in terms of colloidal interactions and adhesion forces, even if the cohesion forces between particles are much weaker for clay particles [Pellenq 2008], due to the difference of constitute binder (no hydraulic reaction occurs). To improve the material workability and mechanical properties, a careful control of the rheology of the clays requires a better understanding of colloidal interaction between particles [Kolver 2011] and knowledge transfer from the fundamental physics of grain and colloidal to the civil engineering [Yammine 2008]. In this way, recent attempts have been made to fluidify earth material in order to be able to cast it with the same techniques as concrete. The French laboratory CRATerre and the University of Mokpo [Kang 2011] have experimented castable earth where cement plasticizers are used to reduce the yield stress and around 8 to 10 wt% of cement is used to allow the setting (sufficient strength in order to remove the formwork). By using a consequent amount of cement, the process works but the involved mechanisms are still unclear: the clay behaviour in presence of cement and the effect of plasticizers on clay during the dispersion have to be understood. Furthermore, too much cement is still used. Alternative cementitious binders, such as Calcium Sulfo Aluminate cement (CSA), can thus be used instead of cement in order to have a reduced environmental impact. The introduction of CSA in a clay based matrix also overcomes difficulties of high pH and high Calcium content of Ordinary Portland Cement (OPC), by formation of ettringite and no precipitation of portlandite.

Furthermore, as unique binder in earth, clay has a permanent negative surface charge and a variable positive charge at the edge. Depending on the pH and the ionic strength, the edge positive surface can be modified. With the help of organic plasticizer such as polycarboxylate ethers (PCE), dispersant commonly used in cement industry, the surface interaction of clay changed and the deflocculation is reached to obtain a flowable paste. The difficulty is then to be able to modify their behaviour after the clay based concrete has been casted, in order to remove the formwork.

In this paper, we study the behaviour of earth materials with and without CSA at fresh and hardened state. We highlight the ability of cement plasticizer to deflocculate clay particles, effect enhanced by the presence of CSA. It is shown that this alternative binder used for the first time in literature, besides improving earth material fluidity, allows providing to the material a sufficient compressive strength at early age. At the hardened state, the material provides sufficient strength to be used as a structural building material for low rise housing (up to 2 storeys).

2 MATERIALS AND PROCEDURES

2.1 Materials:

A commercially available earth for plastering was used in this study. It contains 55% of fine particles (< 100 µm) (Figure 1), including clays and silt. The high range water reducing agent (HRWRA) was a polycarboxylate ethers (PCE) type polymer from cement industry, Viscocrete 3082 (Sika©). In order to estimate the effect of the HRWRA on earth material deflocculation, various amount of PCE were added to the mix (0.5%, 1% and 2%). As in concrete, the water to clay ratio plays a major role. In this study, this ratio was kept low (0.35) to obtain an initial material sufficiently thick, with low porosity and to be able to evaluate the efficiency of admixtures. Furthermore, the impact of CSA, an alternative cementitious binder, from Buzzi Unicem© is studied. This choice is motivated by its lowest environmental impact compare to OPC.

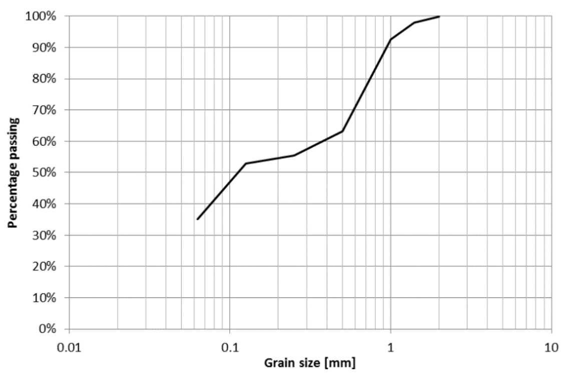

Figure 1: Particle size distribution of the studied earth material

2.2 Procedures

Rheological characterization

The rheological behaviour was measured using slump flow test. Directly after mixing, a cylindric mold was filled with the mix and lifted. By measuring the diameter of the sample after flow stop, it is then possible to convert spread into material yield stress thanks to analytic solutions [Roussel 2012] [Roussel and Coussot 2005].

Setting and hardened properties

In parallel of rheological characterization, setting properties at early age of mix designed materials were tested thanks to a penetrometer, measuring setting over time by sampling a specimen at different location and time [Lloret 2013]. Other mix samples were poured into standard moulds (4x4x16) in order to evaluate their mechanical performances. Compression and flexural tests were performed at 24h (just after removing from the moulds), 7 and 28 days.

3 RESULTS AND DISCUSSIONS

3.1 Fresh properties of earth based concrete*:*

The strategy to develop an SCCC based on the deflocuIation and coagulation of earth is doable by investigating the material behaviour and properties at fresh state. It can be seen in Figure 2a that the use of PCE with earth reduces its yield stress but is much less efficient than when CSA is introduced into the mix. Indeed, 5% of CSA decreases drastically the yield stress in presence of PCE. This result can be explained by the effect of Ca^{2+} and high pH content in solution that allow adhesion between negative charged surfaces (DLVO theory). Indeed, as we can see in Figure 2a, an increase of PCE amount decreases the yield stress of earth material due to the adsorption of polymer (negatively charged) at the surface of clays particles involving an electrostatic repulsion and provides steric hindrance that prevent close contact between particles, reducing the magnitude of the attractive forces [Flatt 2004]. It seems that a lower amount of CSA could allow an optimal efficiency and a dosage of 1% of PCE is sufficient to reach the optimal rheology. This experiment shows that it is possible to use PCE from cement industry to deflocculate clay particles (decrease in yield stress) as soon as a small amount of cement is present, allowing to produce a earth concrete which can be poured into a formwork.

3.2 Setting properties of earth based concrete

Concerning the setting, increasing water content allows for an increase in the initial workability, but will induce a larger shrinkage at the hardened state. Therefore, it seems fundamental to be able to work with a clay mixture that has the lowest water content in the fresh state (but still flows) and to remove this water once the material is placed in order to be able to remove the formwork at early age. We tried to remove water by transforming this liquid water into solid through a hydraulic reaction. This strategy, studied by penetrometer measurements, is encouraging as showed in Figure 2b, where early compressive strength is plotted as a function of time. Thanks to this methodology, we can clearly follow the early stage of the setting of the various tested materials: earth mixture with and without CSA. The choice of this type of cement, besides its lower environmental impact, was justified by the fact that the hydration of CSA takes 18 molecules for the formation of ettringite ($C_4A_3\underline{S}$ + 18H → $C_3A.C\underline{S}.H_{12}$ + 2 AH_3) so the water consumption per gram of CSA is higher in comparison to water binder during OPC hydration (10 to 30 *vs* 5 to 8). It is therefore proposed that the cement setting will allow to chemically bind the water used to allow earth to flow in its fresh state. Indeed, during the hydration of CSA, ettringite is formed in the accelerated phase and act as a “sponge” by pumping water [Winnefeld 2010] resulting of an increase in early compressive strength.

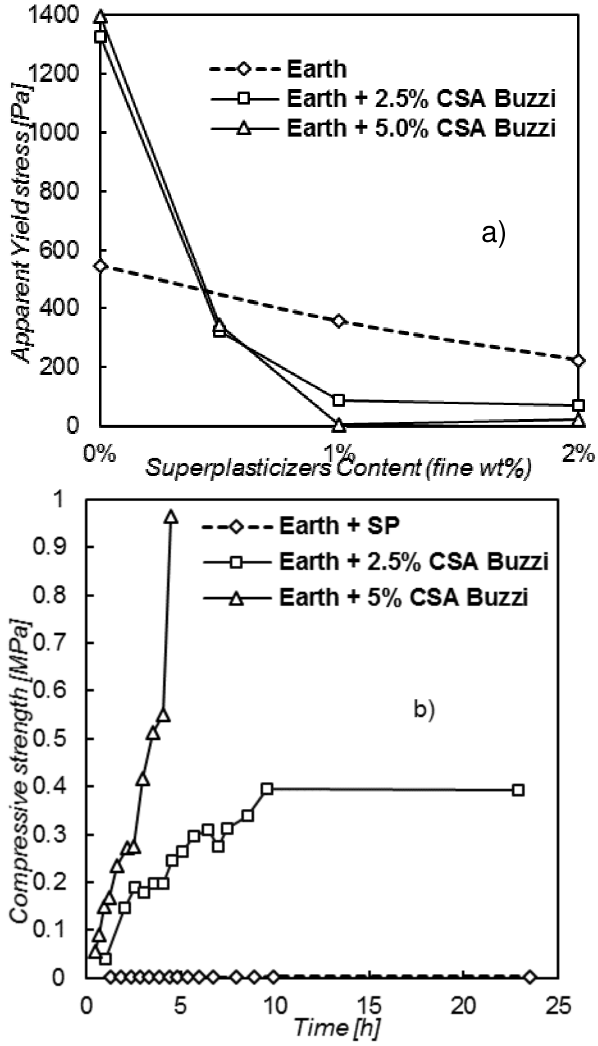

Fig 2: a) effect of SP and CSA cement on earth with 55% of fine particles and b) early development of compressive strength over time measured by penetrometer

In Figure 2b, we can clearly observe that, without the addition of CSA, no change in compressive strength occurred. Furthermore, a material must display a minimum compressive strength of the order to 1 MPa at 24h to be able to remove the mould. This result shows that it would not be possible to remove the formwork of clay based concrete if only PCE was used. By the addition of 5% of CSA in the earth mixture, a compressive strength of 1 MPa is reached during the first hours (~5h), and the demoulding is made possible. At lower content (2.5% of CSA), the same phenomenon occurs but with a reduced amplitude. A maximum potential is reached after 10 hours at 0.4 MPa. It has to be noted that these final strengths could be higher if the initial water content would have been reduced.

3.3 Hardened state of earth based concrete:

All these experiments have been performed with a low water to fine ratio (W/F=0.35). However, the compressive strength of the earth concrete can be increased when the water content of the paste is reduced (Figure 3).

Indeed, compressive strength of earth material is known to vary with the dry density and the clay content for compressed earth block [Morel 2007]. By reducing the water to binder ratio, the porosity and permeability of the material decrease, leading to a higher compressive strength. We can show here that the same results can be achieved with a material poured in a formwork, rather than compacted. It is not surprising as it follows the physic of grains that has been successfully applied to concrete [deLarrard 1994]. It can also be noted that once the formwork is removed, the clay based material can dry which increases its mechanical performance (Figure 3).

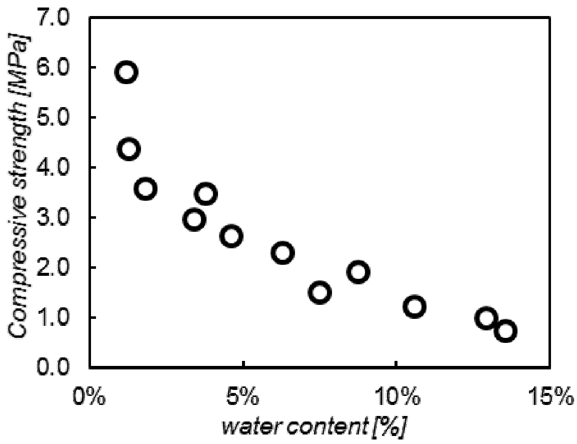

Figure 3: Compressive strength as a function of water content in sample. (5% CSA and 1% PCE)

The material that we have prepared has a final compressive strength of 1 to 6 MPa. As cement was used in order to chemically remove water from the mix and not to provide a higher strength to the material we do not expect to have a much higher strength even when mix design will be optimized (reduced water content, better granular optimization and density packing). 5 to 8 MPa is therefore the target strength that we will be able to reach for the SCCC.

3.4 Environmental performance of the new earth based concrete:

The material developed in this study has a much lower strength than a conventional concrete, and can therefore not be compared to it. However, the strength is similar to concrete blocks and potential applications in terms of construction cost for two storey buildings would be similar. Data on efficient production process for concrete block technologies show that the CO_2 emissions related to the production is around 15 kg $CO_{2\ eq.}$ per m^2 of wall *[EPD Concrete block 2014]*. For the future SCCC developed with the studied technology, one can consider that we will add coarse aggregates to the mortar in order to have 50% of paste and 50% of aggregates. The mix design and their relative carbon footprint are shown in table 1 for SCCC and concrete block. Data for environmental impacts of components have been taken from Ecoinvent v2.

It is interesting to see that first both products have very similar environmental impact. Knowing that concrete blocks are among the products with the lowest environmental impact per square meter and that the one presented in table 1 is concrete block produced with energy efficient process, the SCCC proposed in this study is therefore a promising solution. Actually, most concrete blocks produced in developing countries have a higher cement content.

Tab 1: Mass and CO_2 emissions associated with the production of 1m^2 of wall with a concrete block technology and SCCC

	Functional unit = 1m^2 wall			
	Concrete block technology		**Self-Compacted Clay Concrete**	
	Mass *(kg)*	**Environment** *(kg CO_{2eq})*	**Mass** *(kg)*	**Environment** *(kg CO_{2eq})*
Cement	20.8	14.6	9.0	5.0
Chemical admixture	0.4	0.3	11	7.7
Earth Mortar			323	1.0
Aggreagates (Sand and gravel)	196.6	0.6	230	0.7
Water	10.8	0.0	65	0.0
Total environmental impact	**15.45**		**15.5**	

Furthermore, it seems important to point out that among the main contribution to the environmental impact, cement is not anymore the main one (compared to typical concrete block or concrete). In our product, due to the very small amount of cement used, the plasticizer becomes a significant contributor. It means that, at the difference with all cement based product, the SCCC developed here would have an improved environmental footprint when a more environmentally plasticizer would be used. Transfer of technologies not only from cement and concrete technologies but also from vernacular earthen construction could be a very promising option. Actually, it is known that during centuries some natural products were used as stabilizers, such as blood, urine, manure, casein, animal glue and plant juices [Vissac 2012]. Many innovative and environmentally friendly earthen materials have been developed through the use of biopolymers in various constructive traditions. Among all these biopolymer molecules, some of them can act as dispersing agents. This is the case of some organic acids like humic acid that can deflocculate montmorillonite particles [Majzik 2007]. Some tannins, which are polyphenolic molecules, can also play this role of dispersant [Olphen 1963].

4 CONCLUSION AND PERSPECTIVES

Strategies that have been tested allow producing a material that can flow and be demoulded after 24 hours. Indeed the PCE used plays an important role on the deflocculation of the clays and allows SCCC: Self-Compacted Clay based Concrete. The deflocculation role is more accentuate when the amount of calcium ion is high and the pH alkaline due to CSA. Then the transfer of physics and rheology principles used in concrete science can be used for clay based concrete. The use of CSA instead of cement is promising firstly due to its capacity to remove faster water and lower shrinkage during drying. More, we showed a rapid strength gain but a low impact on the final mechanical strength. The environmental assessment performed on the first prototype shows that it has a relatively low environmental impact and that it can be compared to concrete blocks. However, at the difference with concrete block, the environmental impact associated with cement compared to chemical admixture is very small, showing that further improvement in term of CO_2 emissions might come from a better used of plasticizers. In particular, using natural plasticizers which have often been used in vernacular earthen construction such as tanins would be a future promising research option. Finally, these initial experiments on the setting of the self-compacting clay concrete open a lot of questions on the mechanisms involved. The removal of the water needs to be understood in terms of chemically and physical bounding phenomena, cement reaction and drying.

5 ACKNOWLEDGMENTS

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