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Self-Compacted Clay Based Concrete (SCCC): Proof-of-Concept

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Abstract: Construction using earth is gaining interest in developed countries, whereas this practice is common in Africa and was more common in Europe 200 years ago. The forecasted increasing demand for cement in emerging countries has created the need for alternative building materials. In this study, recent cement and concrete technologies are transferred to earthen constructions to create a Self-Compacted Clay Concrete. We showed that the use of a superplasticizer (SP) with earth alone reduced the yield stress and was more efficient when cement was added. The optimal rheology was reached with 1% polycarboxylate ethers superplastizer and 5% calcium sulfoaluminate cement. The setting was studied with a digital penetrometer. The accelerated phase of the CSA hydration occurred within 6 hours only when 5% of CSA was in the earth mixture. Cement transformed the interstitial liquid water between particles into chemically bound water that did not affect the flow in the fresh state. Mechanical tests on the dried self-compacting-clay concrete showed that the compressive strength was increased by a factor of four when reducing the initial water content. The compressive strength of earth material is known to vary with the dry density and the clay content in the compressed earth block. The novelty of our approach is that the identical results can be achieved with a material poured in a formwork rather than compacted. Finally, the carbon footprint of the solution was evaluated, and the results show that this new material is competitive with current construction techniques.

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Self-Compacted Clay Based Concrete (SCCC): Proof-of-Concept

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Abstract

Construction using earth is gaining interest in developed countries, whereas this practice is common in Africa and was more common in Europe 200 years ago. The forecasted increasing demand for cement in emerging countries has created the need for alternative building materials. In this study, recent cement and concrete technologies are transferred to earthen constructions to create a Self-Compacted Clay Concrete. We showed that the use of a superplasticizer (SP) with earth alone reduced the yield stress and was more efficient when cement was added. The optimal rheology was reached with 1% polycarboxylate ethers superplastizer and 5% calcium sulfoaluminate cement. The setting was studied with a digital penetrometer. The accelerated phase of the CSA hydration occurred within 6 hours only when 5% of CSA was in the earth mixture. Cement transformed the interstitial liquid water between particles into chemically bound water that did not affect the flow in the fresh state. Mechanical tests on the dried self-compacting-clay concrete showed that the compressive strength was increased by a factor of four when reducing the initial water content. The compressive strength of earth material is known to vary with the dry density and the clay content in the compressed earth block. The novelty of our approach is that the identical results can be achieved with a material poured in a formwork rather than compacted. Finally, the carbon footprint of the solution was evaluated, and the results show that this new material is competitive with current construction techniques.

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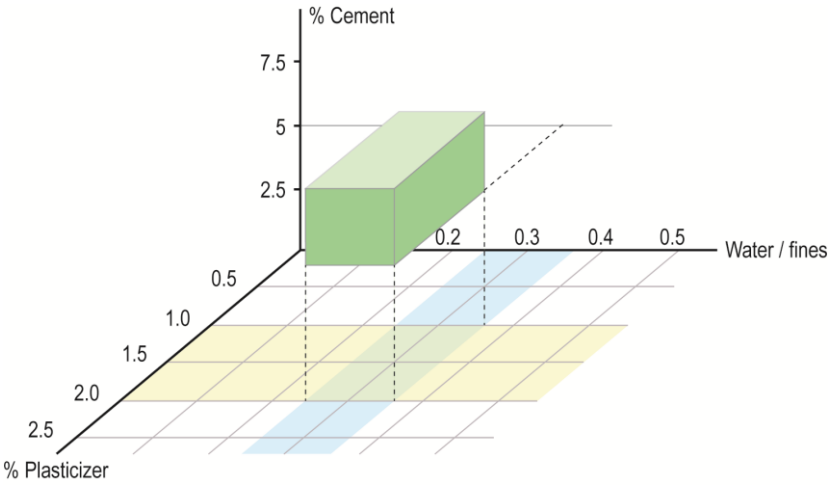
Graphical Abstract



Highlights

- Self-compacting clay concrete using a superplasticizer and CSA cement
- Optimization of the strength with low cement and water content
- Improved stabilized soil

Keywords

Self-compacting clay concrete, sustainability, construction, earth

1. Introduction

Traces of earthen architecture date from up to 10,000 years ago, and this practice is still used in most climates and societies (Pacheco-Torgal et al., 2012). With no transport needs and with infinite recycling possibilities, earth is one of the building materials with the lowest environmental effects (Sameh, S.H., 2014). The forecasted demand increase for cement in emerging countries creates the need to identify alternative building materials because of the effects of cement production on global warming and the limitation of the resource. Rammed earth is a sustainable natural building material with a good thermal conductivity and thermal mass (Hall and Allinson, 2009). Earth plasters offer hygrothermal comfort and a warmer tactile sensation than cement (Melià et al., 2014). However, a wider use in construction is often hindered by the cost and time requirements of conventional earth construction techniques.

Self-compacting concrete was a major breakthrough in the 1980s because this material enables prefabricated elements. Self-compacting concrete is place-able under its own weight (de Larrard, 1999). Additionally, self-compacting concrete contains more water, superplasticizer, powder and less and finer gravel than conventional vibrated concreted (Hüsken and Brouwers, 2008).

Recent cement and concrete new technologies and developments in the ceramic industry can be transferred to earthen construction to create a Self-Compacted Clay Concrete (SCCC). The questions that need to be addressed for a reliable production of a self-compacting clay concrete can be separated into two main aspects: the deflocculation of clays to allow the flow of the grain assemblage (stage 1) and the setting of the material (stage 2).

Superplasticizers ensure the fluidity and workability of the concrete. These chemicals are polymeric dispersants that act as “chemical spices” by changing the interfacing properties in

the system, reducing the yield stress during constant solid content or increasing the solid content for a constant yield stress (Flatt et al., 2012). Polycarboxylate ethers (PCEs) polymers are the most recently developed superplasticizer; PCEs have mainly carboxylic groups and non-ionic side chains of polyethers covalently attached to a polymeric anionic backbone (Flatt and Schober, 2012).

Earth material can be seen as a grain assemblage identical to concrete. Therefore,, the mechanical and rheological considerations for concrete are likely transferable. Clay is an inorganic charged particle; the surface interaction of clay can change in the presence of organic plasticizers, similar to cement particles. Therefore, a flowable paste is possible when an optimal interaction between clay and plasticizer is found. Furthermore, alternative cementitious binders can be used instead of cement to reduce the environmental effects and overcome the difficulties of high pH and high calcium content of OPC when introduced in a clay-based matrix. CSA is a promising low-CO_2 alternative to Portland cement because of its lower clinkering temperature (Gartner, 2004; Juenger et al., 2011). CSA reacts faster with more water than OPC, and hydration heat evolution occurs between 1 and 24 h, which indicates a fast setting.

The aim is then to provide a proof of concept for a self-compacting clay concrete by investigating the mechanical properties from the fresh liquid state to the hardened solid state. The objectives for the SCCC are 1) a good workability at the fresh state with low water content; 2) the ability to remove the formwork within 24 h; 3) a compressive strength suitable for wall elements and 4) toward a reduction in the carbon footprint using a minimal amount of cement. From this study, we can define the boundary conditions for the design of self-compacting clay concrete

2. Materials and methods

2.1. Materials

A commercially available earth for plastering (ProCrea) containing 55% fine particles (< 120 µm; including clays and silt) and 45% sand was used in this study. The particle size was measured by wet sieving the finer fraction and monitoring the size with a laser particle analysis (Fig. 1). The high range water reducing agent (HRWRA) was a modified polycarboxylate ethers (PCE) type Viscocrete 3082 (Sika©). To estimate the effect of the HRWRA on earth material deflocculation, various amounts of PCE were added to the mix (0.5%, 1% and 2% by mass of the fines in the earth). Calcium sulfoaluminate cement (CSA), an alternative cementitious binder from Buzzi Unicem©, was used because of its lower environmental effects compared to Portland cement. CSA was dosed at 2.5% or 5% of the earth content.

The mixing procedure for the self-compacting clay concrete was the following: the dried earth plaster and the cement were first homogenized with an ultra-turrax mixer for 30 seconds, the superplasticizer was added to the water, and the liquid phase was added immediately to the dried phase. The mixture was then mixed as a mortar for two minutes with the ultra-turrax mixer, manually for one minute and mechanically again for two minutes or until the materials reach a homogenized consistency.

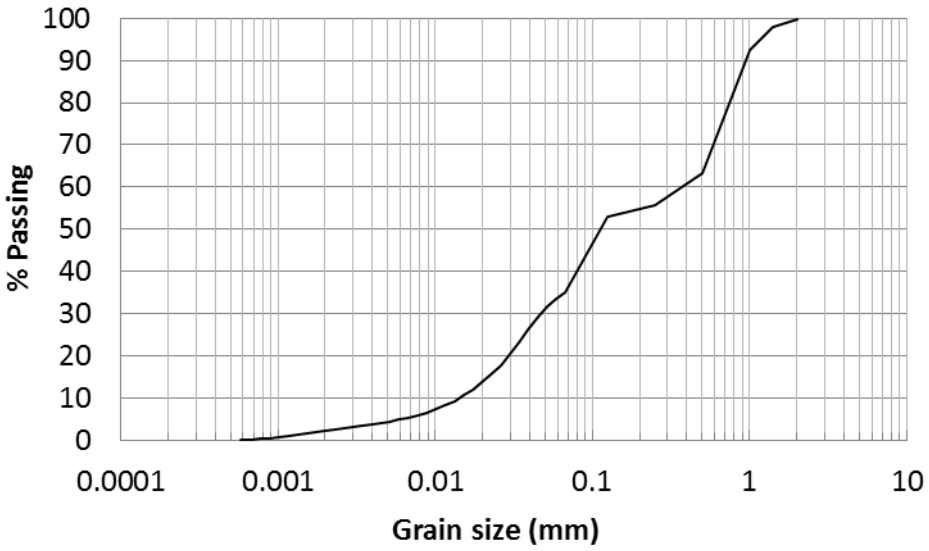


Fig. 1: Particle size distribution of the plastering earth

2.2. Fresh concrete properties

The rheological properties of the fresh earth concrete was measure with a slump test, which is a rapid measurement of the yield stress and is a common measure of the workability of fresh concrete (Roussel and Coussot, 2005). In this practical test, the flow of homogeneous materials varies according to two regimes that depend on the ratio between the radius and the height. In the fresh state, the self-compacting clay concrete can be considered as a continuous material. The slump tests were performed with 12 cm high cylinders on a wet glass surface. In the regime in which the stress variations are significantly more important in the vertical direction than in the radial direction, the yield stress τ_c is calculated from the slump:

$$\tau_c = \frac{\rho g(H - z_c)}{\sqrt{3}} \qquad \text{Eq 1}$$

where H is the height of the test cylinder, z_c is the critical height at which the flow stops, ρ is the density of the materials and g is gravity. In the "spread regime", the radical component of the flow velocity is larger than the vertical component. The yield stress is calculated from the measured spreading distance (R):

$$\tau_c = \frac{225\rho g \Omega^2}{128\pi^2 R^5} \qquad \text{Eq 2}$$

where ρ is the density, g is the specific gravity, and Ω is the volume of the test cylinder.

To evaluate the efficiency of admixtures, the water to binder ratio was maintained constant to compare the earth with the cement mixes. The water to binder ratio was later reduced in the cement mixes once the optimal amount of cement was determined.

2.4 Setting properties

The hardening and setting of cementitious materials is usually determined with empirical tests (Lootens et al., 2009). The setting of the SCCC was measured with a penetrometer, which is a device that drives a needle at a given speed and measures the force required to continue over time. A recently patented penetrometer was connected to a triaxial table and controlled by a Python code (Lloret et al.). The penetrometer measured the setting over time of a larger specimen of cementitious material by sampling at different locations. The specimens of self-compacting clay concrete were 15 cm x 18 cm x 2.5 cm. To obtain the compressive strength, the force recorded was divided by the area of the needle in contact with the earth:

$$\sigma = \frac{F}{\pi r^2 + 2\pi r h} \qquad \text{Eq 3}$$

where F is the force recorded by the penetrometer, r is the diameter of the needle (9.6 mm) and h is the height of the needle. Although the needle was 5 mm thick, only 1 mm was assumed to contribute to the compressive strength.

2.5 Compressive strength

The mechanical strength was tested according to DIN EN 196-1 programmed in the testing device Walter + Bai 502/4000/100. The specimens were prepared with the standard dimensions 40 x 40 x 160 mm in an oiled hakorit formwork. Tests were performed after 1, 7, 28, and 90 days. A minimum of five replicates were used to determine the compressive strength, (often 6 replicates up to 12 replicates when indicated).

2.6 Thermogravimetric analysis

The 6 month aged samples were sieved to 100 µm and left overnight in a vacuum oven at 30 °C and 50 mbar to remove the water physically bound in the sample. The TGA procedure was performed in air: 100 mg of sample was heated at 10 °C per min until 1000 °C. The employed device was the TGA/SDTA851 from Mettler Toledo.

3. Results and discussion

3.1. Step 1: Fresh self-compacting clay concrete

The first step was to determine the conditions required to develop liquid earth with a high workability. The desirable yield stress for the self-compacting clay concrete is in the range of 200-500 Pa (de Larrard, 1999). Lower yield stresses are required because the large aggregates are required to produce a concrete. The use of PCE with earth reduces the yield stress but is less efficient than when CSA is introduced into the mix. In total, 5% CSA decreases the yield stress in presence of PCE (Fig. 2). The optimal rheology was reached with 1% PCE superplasticizer. At this SP content, no difference was noted between 2.5% and 5.0% CSA. The DVLO theory explains the effect of Ca^{2+} in solution that allows adhesion between negative charged surfaces (Yang et al., 1997). An increase in the PCE amount decreases the yield stress of earth material because of the adsorption of the polymer (negatively charged) at the surface of clay particles. This process involves an electrostatic repulsion and provides steric hindrance that prevents close contact between particles, reducing the magnitude of the attractive forces (Flatt, 2004). From the slump tests alone, a lower amount of CSA still produces a paste fluid. This experiment showed PCE from the cement industry can be used to deflocculate clay particles. The PCE decreases the yield stress as soon as a small amount of cement is present, producing an earth concrete that can be poured into a formwork.

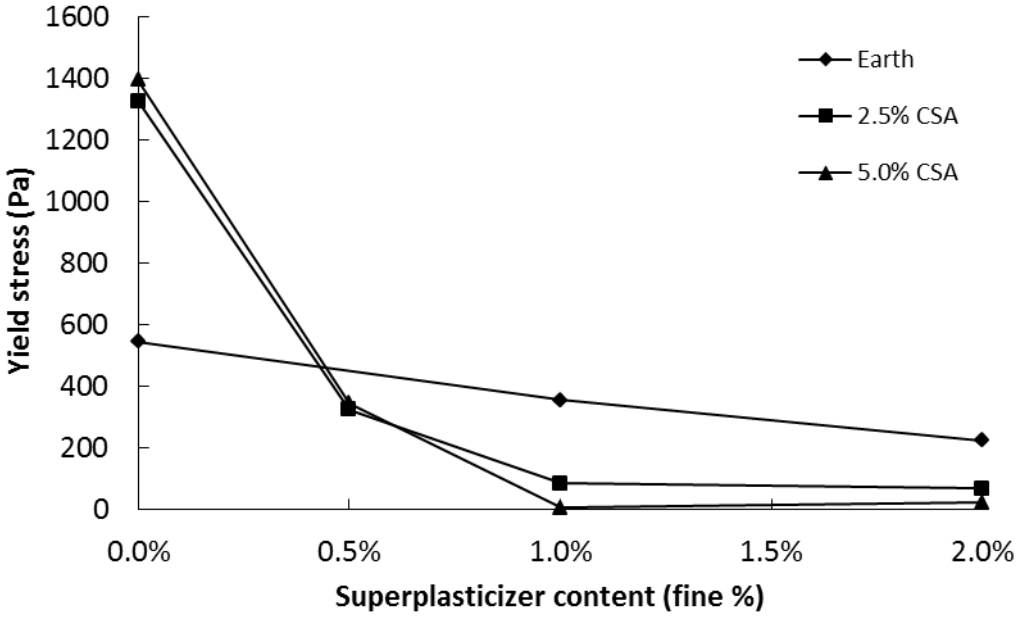


Fig. 2: Yield stress of the SCCC with a superplasticizer and the cement content at a constant water to solid ratio

Increasing the water content allows for an increase in the initial workability, but will induce a larger shrinkage in the hardened state. Therefore, working with a clay mixture that has the lowest water content in the fresh state is required (but still flows), and this water must be removed once the material is placed in the formwork to be able to withdraw the formwork at an early age. With 5% cement, the amount of water can also be reduced from a water/binder ratio of 0.37 to 0.25 (Fig. 3). Because the mixture already contained sand, the yield stress would be suitable for the later addition of aggregates.

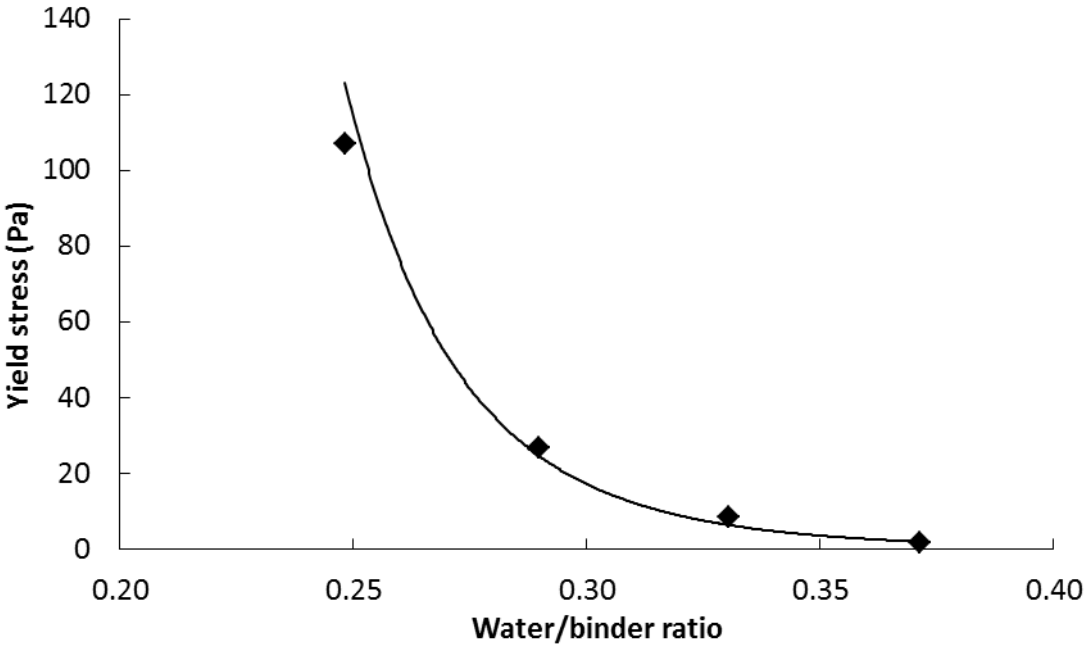


Fig. 3: Reduction of the yield stress with the water/binder ratio (1% SP and 5% CSA)

3.2. Step 2: Setting

The hydraulic reaction of cement transforms the liquid water into a solid. This strategy, studied by penetrometer measurements, followed the early stage of the setting of the various tested materials: earth mixture with and without CSA (Fig. 4). The choice of the CSA cement, in addition to its lower environmental effects, was justified by the fact that the reaction products from CSA consume more water molecules than the one involved in OPC (10 to 30 *vs* 5 to 8). It was therefore proposed that the cement chemically binds the water during setting, allowing the earth to flow in the fresh state. During the hydration of CSA, ettringite is formed in the accelerated phase and acts as a "sponge" by pumping water (Winnefeld and Lothenbach, 2010), resulting in an increase in early compressive strength. This aspect is further discussed in section 4.1 and 4.2. In Fig. 4, the earth, without the addition of CSA, displays no change in compressive strength during the first day. Furthermore, a material must display a minimum compressive strength of 1 MPa at 24 h to be able to remove the formwork. This result shows that the formwork could not be removed from the clay-based concrete if only PCE was used. By adding 5% of CSA in the earth mixture, a compressive strength of 1

MPa is achieved in the first few hours (~6h), and the formwork can be removed. At lower contents (2.5% of CSA), the identical phenomenon occurs with a reduced amplitude. A maximum potential is reached after 10 hours at 0.2 MPa, but to the framework cannot be removed. These final strengths can be higher when the initial water content is reduced, and this figure displayed the development of the liquid earth.

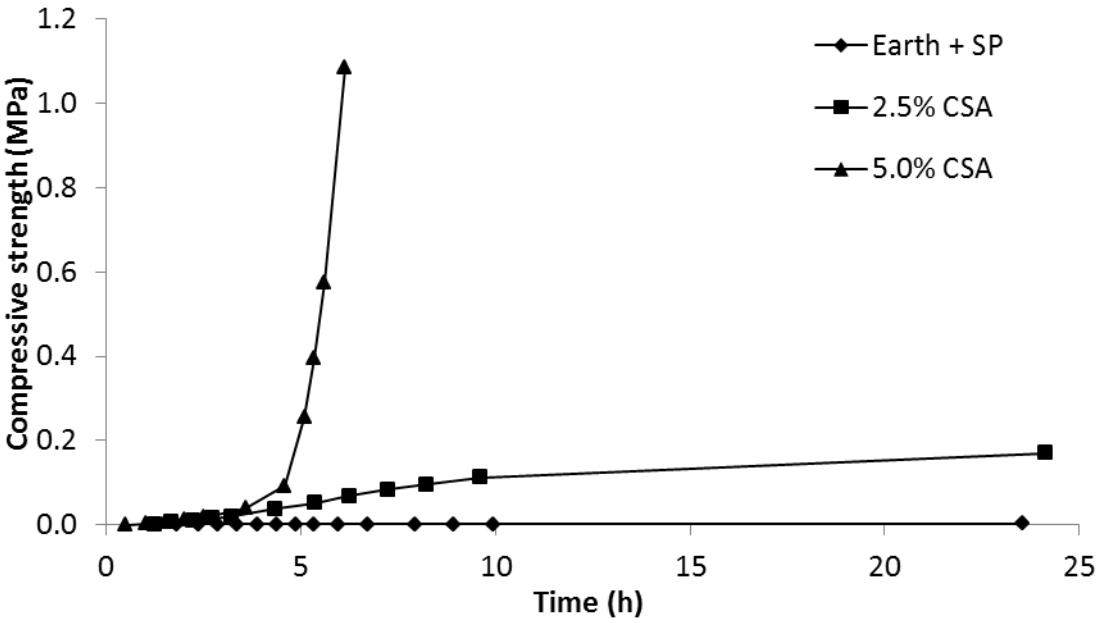


Fig. 4: Early development of the compressive strength (water/binder ratio: 0.37)

3.3. The hardened solid state

The prepared SCCC has a final compressive strength of 2 to 8 MPa depending on the initial water to binder ratio (w/b) (Fig. 5). The compressive strength of the earth alone and the earth with 5% CSA at the water content is comparable (w/b 0.37). Therefore, the cement did not develop mechanical strength. On the first day, the concrete hastened the development of strength. The CSA was more used to chemically remove water from the mix. Once the formwork was removed, the clay-based material could dry, increasing the mechanical performance. The compressive strength of the earth concrete increases with decreasing water content in the paste. Using the superplasticizer and cement developed a fluid behavior in the fresh state at a reduced water content, further increasing the compressive strength. The

compressive strength required 28 days to develop and stabilize at the initial w/b of 0.29 – 0.37. At an initial w/b of 0.25, the strength continued to develop to 8 MPa after 90 days in the 12 replicates. Optimizing the cure would further reduce the variability. The higher mechanical performance was attributed to the reduction in the water content. Our experimental results for the flexural strength correlated well with the compressive strength (r^2: 0.92-0.96), and the flexural strength at 90 days corresponded to 27% of the compressive strength, as an average of the four series.

The compressive strength of earth material varies with the dry density and the clay content in the compressed earth block (Morel et al., 2007). By reducing the water to binder ratio, the porosity and permeability of the material decrease, producing a higher compressive strength. Reducing the capillary pores is essential for the mechanical characteristics and durability of the hardened concrete (Hüsken and Brouwers, 2008). We show that the identical results can be achieved with a material poured in a formwork rather than compacted. This result is expected because the physic of the grains is identical to those that have been successfully applied in concrete (de Larrard, 1999). We do not expect to have a much higher strength even when the mix design is optimized (reduced water content, better granular optimization and density packing). The target strength is therefore 5 to 10 MPa for the SCCC.

The mechanical strength of the SCCC is comparable with a stabilized soil or stabilized rammed earth. The initial w/b is set at 0.37-0.33, displaying a comparable compressive strength of 3 MPa after 28 days for soil stabilized with 5% CEM 1 cement (Bahar et al., 2004). In that article, the compressive strength reached a plateau of 6 MPa even when using 20% cement. In another study of rammed earth stabilized with cement, 10% cement was required to reach 3 MPa (Jayasinghe and Kamaladasa, 2007). With our approach, we were able to increase the strength further by reducing the water in the sample, whereas maintaining the amount of cement at 5% earth (only 4.2% of the total mass) by a technology transfer from the self-compacting concrete technology.

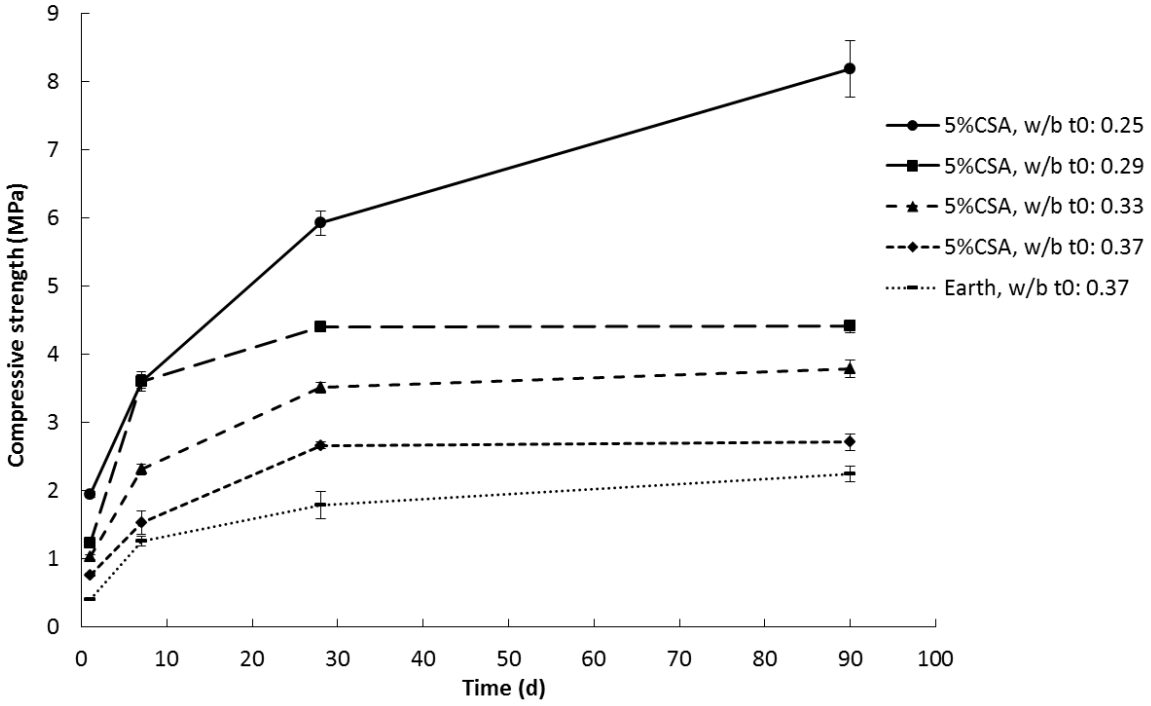


Fig. 5: Compressive strength development with time (samples with CSA contained superplasticizer)

4. Discussion

4.1 Mechanism for the development of mechanical resistance

The mechanisms for the development of the mechanical strength are the hydration of the cement and the evaporation of free water in the mortar. The water content in the specimen can be calculated with the following three equations:

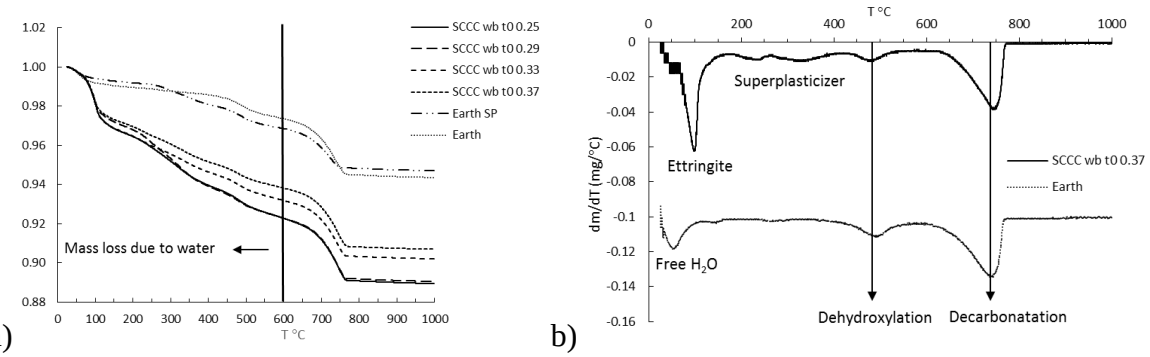
$$Water\ content = \frac{W_{sample}}{M_{test}} \qquad \text{Eq 4}$$

$$W_{sample} = W_{in} - W_{evaporated} \qquad \text{Eq 5}$$

$$W_{evaporated} = M_{initial} - M_{test} \qquad \text{Eq 6}$$

where W_{sample} is the water remaining in the sample, W_{in} is the water initially in the sample, $W_{evaporated}$ is the water evaporated during the curing/drying of the sample between the casting time and the testing time, $M_{initial}$ is the calculated initial mass of the mortar, and M_{test} is the

mass of the sample on the day of the test. The water content includes the water that is physically and chemically bound. A thermogravimetric analysis (TGA) determined the water that is chemically bound in the samples (Fig. 6). TGA differentiated the samples with CSA from those with earth only or earth and SP. In total, 0.6% of the water was physically bound to the sample, unable to be removed with the normal humidity. Because the samples were previously conditioned in vacuum conditions (50 mbar and 30 °C) to remove the water, the mineralogy was less affected and this water was assumed to be adsorbed when moving the sample from the oven to the TGA. In earth alone, an additional 2.0% of water was chemically bound in the -OH groups of the clay structure. The mass loss because of the superplasticizer represented 0.5%. With the CSA, an additional 3.0% to 4.6% of water was chemically bound to the fine particles. The amount of water chemically bound to the CSA is 0.4 gram/ g CSA. With 5% CSA, approximately 1.7% of the water would be bound to the CSA, notably in the ettringite formation (visible in the TGA by the mass loss between 50 and 120 °C) in the early days and in monosulfate and stratlingite formations later in the process (Winnefeld and Lothenbach, 2010). The remaining amount results from the additional chemical water binding mechanisms in the matrix linked with the presence of the CSA.



a) b)

Fig. 6. a) Mass variation as determined by a thermo-gravimetric analysis, b) derivative mass change

The mechanical strength correlated well with the interstitial water content, which was calculated as the following:

$$Pore\ water = Water\ content - fines\ content\ x\ W_{TGA} \quad \text{Eq 7}$$

where W_{TGA} is the mass loss between 25°C and 600°C measured for the fines of the sample with CSA minus the mass loss of the earth and superplasticizer. The fines content was taken as 55% (from the initial earth mix). The interstitial water in the sample increased with the value of the compressive strength more than the age of the sample (Fig. 7). For example, samples with higher initial water content had the identical strength at 28 days as samples with lower water content after 7 days. Thus, the strength depended on the interstitial pore water in the sample. The only point that does not correlate well is the mortar at 8 MPa because of the additional strength of the CSA.

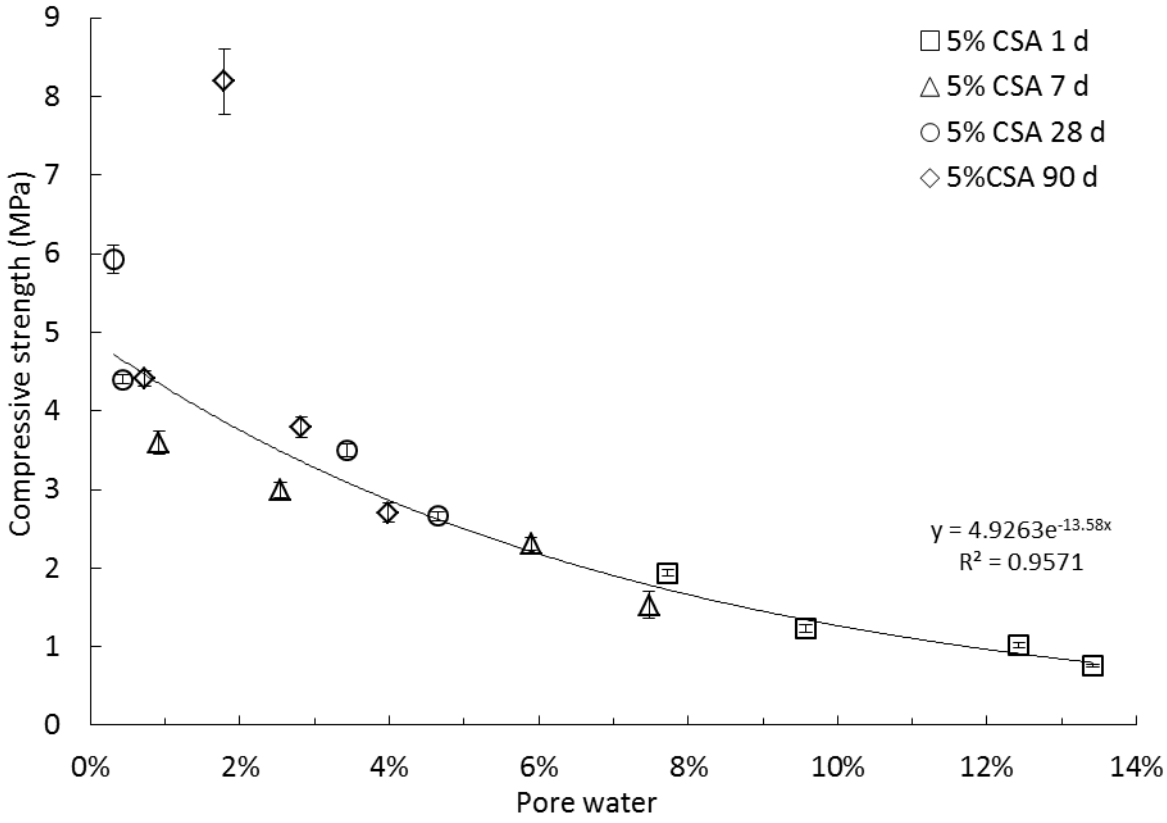


Fig. 7: Variation of the compressive strength with the free water in the sample (the sample contained superplasticizer and CSA)

4.2 Relative contribution of the different components to the mechanical strength

The self-compacting clay concrete is an improvement compared to soil stabilized with cement because the identical mechanical performance is achieved with almost half of the cement. The mechanical performance is comparable for the SCCC with the initial w/b of 0.25 with the compacted cement stabilized soil with 10% cement with an assumed w/b of 0.4 (8.2 MPa and 7.6 MPa, respectively). The overall superplasticizer content in the SCCC was 0.5% of the total initial mass (1% of fines), reducing the dry cement content by 2.7%. The proportion was rebalanced by increasing the initial water content by 0.6% and the earth content by 1.7% in the SCCC when compared to the stabilized soil. The two are compared in Fig. 8 based on the component responsible for the compressive strength (top) and on a mass basis (below). The relative contribution of the SCCC was determined by comparing the strength of the different mortars, i.e. 1) liquid earth; 2) liquid earth with superplasticizer; 3) liquid earth with superplasticizer and CSA; and 4) liquid earth with reduced water, superplasticizer and CSA. For the compacted stabilized soil, the strength of the compacted soil was compacted to the strength of the cement stabilized soil, following reported experimental results (Bahar et al., 2004). A slight change in the composition allowed the reduction of the cement content and the diversification of the materials contributing to the strength. Adding more water in the earth mix provided additional bonding forces at the particle contact interface. From geotechnical engineering, capillary potential dominates granular soil around the sand particles, whereas the adsorption potential is more significant in clayey soils at low water content. A gradual transition is noted between the capillary and adsorption potential as the distance between the solid particles surface reduces (Gens, 2010). From the TGA, the capillary and adsorption potential were lightly cemented to chemically capture the water over time in the presence of CSA. From a strength perspective, the use of superplasticizers also increased the strength of the liquid earth by nearly 2%. The CSA itself provided approximately 8.6% of the strength, and once the water was reduced with the use of superplasticizer, the packing, density, and compressive strength increased.

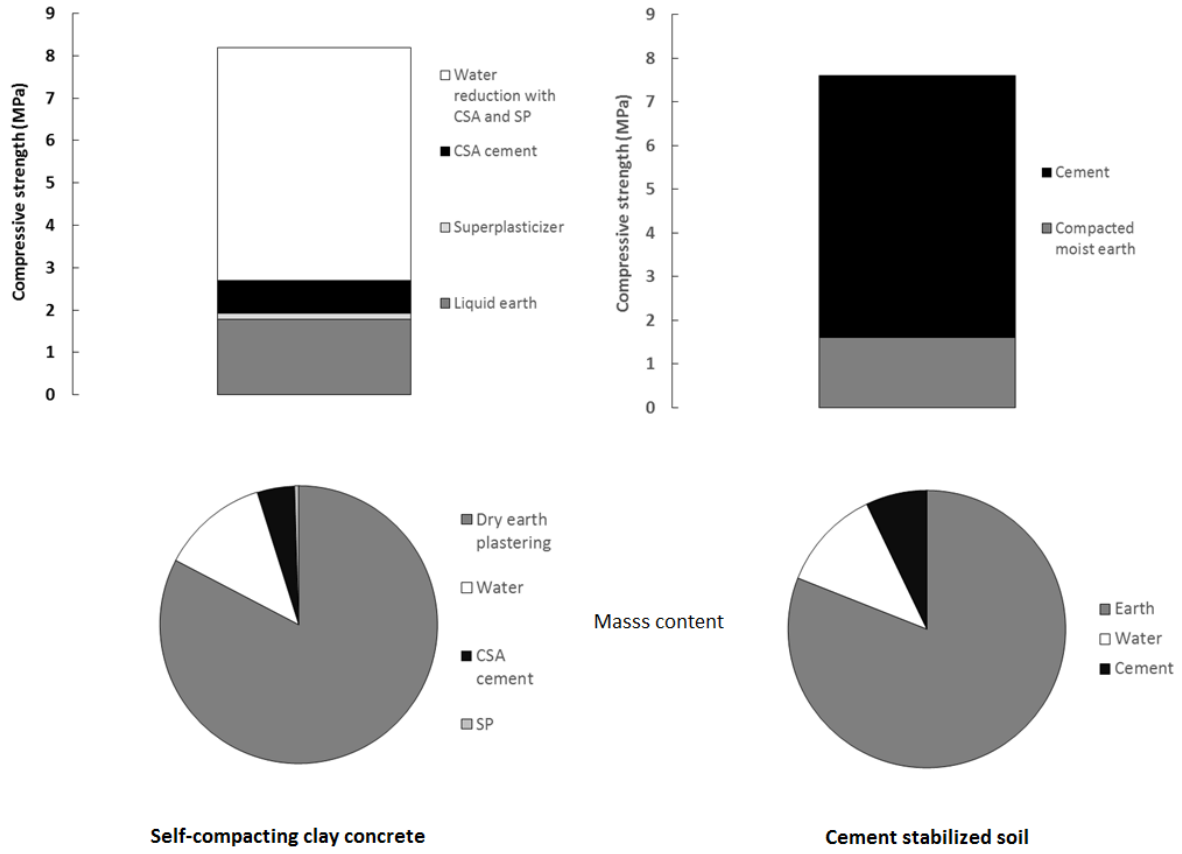


Fig. 8: Comparison between self-compacting clay concrete and cement stabilized soil on a compressive strength (top) and mass (below) basis

4.3 Environmental effects

The material developed in this study had a strength similar to concrete blocks and similar potential applications in terms of construction cost for two story buildings. However, this new material had a lower strength than conventional concrete and can therefore not be compared to conventional concrete. Data on the efficient production process for concrete block technologies show that the CO_2 emissions related to the production is approximately 15 kg $CO_{2\ eq.}$ per m^2 of wall (Base INIES, 2013). For the future SCCC developed with the studied technology, we will add coarse aggregates to the mortar to produce 50% paste and 50% aggregates. The mix design and the relative carbon footprint are shown in table 1 for SCCC and concrete block. Data for the environmental effects of components were taken from Ecoinvent v2.

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

	Functional Unit = 1 m^2 wall			
	Concrete block technology		Self-Compacting Clay Concrete	
	Mass	Impact	Mass	Impact
	kg	kg CO_2 eq.	kg	kg CO_2 eq.
Cement	20.8	14.6	14	9.8
Chemical admixture	0.4	0.3	5.4	4.1
Earth mortar			350	1.1
Aggregate (sand & gravel)	196.6	0.6	200	0.6
Water	10.8	0.0	65	0.0
		15.5		15.6

Both products have similar environmental effects. Knowing that concrete blocks are among the products with the lowest environmental effects per square meter and that the concrete block presented in Table 1 was produced with an energy efficient process, the SCCC proposed in this study is therefore a promising solution. The majority of concrete blocks produced in developing countries have a higher cement content. In a comparative study of the earth and conventional industrial plasters, the earth plaster outperformed the industrial plasters for all indicators: the cumulative energy demand, global warming potential and ecological footprint (Melià et al., 2014).

Furthermore, among the main contributions to the environmental effects, cement is not the only one (compared to typical concrete block or concrete). In our product, because of the small amount of cement used, the superplasticizer becomes also a significant contributor. By contrast with all cement based product, the SCCC developed here would have an improved environmental footprint when a more environmentally friendly plasticizer is used.

4.4 Boundaries conditions for the self-compacting clay concrete

From this study, the boundary conditions for the production of the self-compacting clay concrete (SCCC) can be defined. The particle size is an initial requirement of the SCCC. From the self-compacting concrete, a higher quantity of fine materials is required in addition to superplasticizers to ensure that the paste is viscous enough to overcome segregation. Otherwise, a viscosity agent is required to play the role of the fine particles (de Larrard, 1999). A larger number of grain-to-grain contacts in the finer range is desirable to increase the cohesion in the materials (Hüsken and Brouwers, 2008).

To achieve the required workability, the amount of water must be dosed. The initial slump test shows the amount of water needed to initiate the self-compaction behavior. The second quantity to optimize is the superplasticizer content required to render the earth liquid. Slump tests were sufficient to screen these effects because we used Roussel's equation to convert the spread into a yield stress (Roussel and Coussot, 2005). Between 1% and 2% of superplasticizer were required to lower the yield stress (Fig. 2), which can be transposed in the boundaries conditions in Fig. 9. The presence of a superplasticizer does not affect the dosage of aggregates (de Larrard, 1999). The amount of water was then optimized when the cement and SP were in the mixture. The lower water content at the fresh state is desirable in any concrete to reduce cost (de Larrard, 1999). Thus the water/binder ratio was then reduced from 0.37 to 0.25. The paste was still fluid enough to later add coarser aggregates. The last important criterion was the minimal amount of cement required to remove the formwork easily. The setting test showed that 5% CSA cement was needed for a faster setting. Thus the paste for the SCCC contains a w/b of 0.37-0.25, superplasticizer between 1-2% fines and between 2.5 and 5% cement.

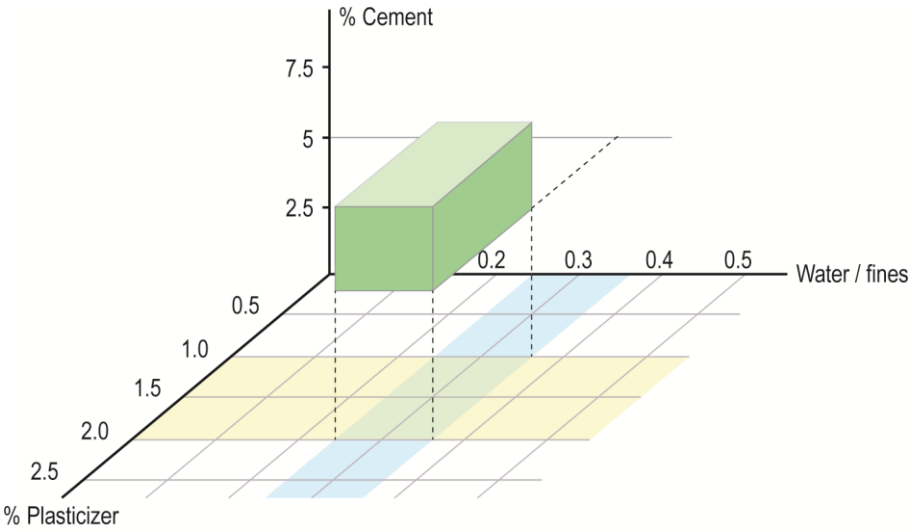


Fig. 9: Boundary conditions for the water, superplasticizer and cement content for the self-compacting clay concrete

4.5 Perspective on the development of new materials

The use of superplasticizer with enhanced clay tolerance will become important, notably when working with natural earth mixes that can contain more smectite. PCEs superplasticizers are known to intercalate the clay structure easily by the PEO side chains (Lei and Plank, 2012; Ouellet-Plamondon et al., 2014). Novel PCEs with hydroxyl alkyl lateral chains enhanced the dispersion in cement in the presence of montmorillonite clay (Lei and Plank, 2012); thus, a lower amount of superplasticizer can be used to lower the yield stress in the fresh state, thereby improving the environmental balance. Additional studies on the links between the type of superplasticizer, water evaporation, cement type and mechanical strength development are required to further optimize the conditions for the SCCC.

The use of clay as nanofillers is gaining interest to achieve performance criteria (Nehdi, 2014). For example, non-modified nano-kaolinite and nano-smectite enhanced the formation of C-S-H by providing nucleation surfaces in Portland cement paste (Lindgreen et al., 2008). Ultrafine silicates allow the engineering of the porosity and the specific surface area of the dried cement paste. The use of clays was also promoted in self-compacting concrete to reduce the formwork lateral pressure, increasing because of the high fluidity and placement rate (Kim

et al., 2010). SEM images of our samples of SCCC also showed that the porosity of the materials can be decreased further by studying the granular packing.

We desire materials that are suitable for rapid production by simple modification of the technology used in the concrete construction industry. From the mechanical strength criterion, producing compressed earth bricks and earthen panels is possible. In Fig. 7, the SCCC at an initial w/b of 0.25 adsorbs water with time; therefore, building should be able to store the additional moisture. Additional studies are required to determine whether the moisture could be released in drier conditions. For wall elements, a part of the cement content can be replaced with plaster to remove the water; our trials showed that the mechanical strength is better at a lower w/b because plaster requires less water to hydrate. Further trials would be also possible with limestone, and a lower w/b is advisable. To improve the mechanical resistance more in the range of the SCC, optimizing the packing density would be the next step; the packing density is the ratio of the solid volume to the total volume of the container (de Larrard and Sedran, 2002). Further optimization of the cohesion strength in clays is possible.

The transfer of technologies not only from cement and concrete technologies but also from vernacular earthen construction could be a promising option. Many innovative and environmentally friendly earthen materials have been developed through the use of biopolymers in various constructive traditions. Among all these biopolymer molecules, several can act as dispersing agents. This dispersion is noted for several organic acids, such as humic acid, that can deflocculate montmorillonite particles (Majzik and Tombácz, 2007). Select tannins, which are polyphenolic molecules, can also act as a dispersant (van Olphen, 1977).

5. Conclusion

The tested strategies produced a flowing material that can have the formwork removed from after 24 hours. The PCE superplasticizer played an important role in the deflocculation of the clays and allowing the production of SCCC: Self-Compacted Clay based Concrete. The defloculation role was more accentuated when the amount of calcium ions is high and the pH is alkaline because of the CSA. The CSA cement had the capacity to remove more water per gram of cement than Portland cement. The transfer of physics and rheology principles used in concrete science can then be used for clay based concretes. The use of CSA instead of cement is promising because of its capacity to remove faster water and the lower shrinkage during drying. Additionally, we showed a rapid strength gain with a minimal effect on the final mechanical strength.

Overall, this work provided initial boundaries for the doses of the water, superplasticizer and cement to produce SCCC. The superplasticizer and cement were essential in reducing the water content and ensuring self-compaction. CSA was required for water uptake and for the development of the mechanical strength. Optimization of the cure would further improve the performance of the materials.

The environmental assessment performed on the first prototype shows that the material has a relatively low environmental effect and it can be compared to concrete blocks. By contrast with concrete blocks, the environmental effects associated with cement compared to chemical admixture is small, showing that further improvement in terms of CO_2 emissions might result from a better use of superplasticizers. 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 establish questions on the mechanisms involved. The removal of the

water can be further understood in terms of the chemically and physical bounding phenomena, cement reaction and drying.

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24 February 2015

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D. Huisingh
Editor-in-Chief, Journal of Cleaner Production
University of Tennessee, Knoxville, Tennessee, USA

Object: **Self-Compacted Clay Based Concrete (SCCC): Proof-of-Concept**

Dear Professor Huisingh,

I write you to submit the article "**Self-Compacted Clay Based Concrete (SCCC): Proof-of-Concept**" to the Journal of Cleaner Production.

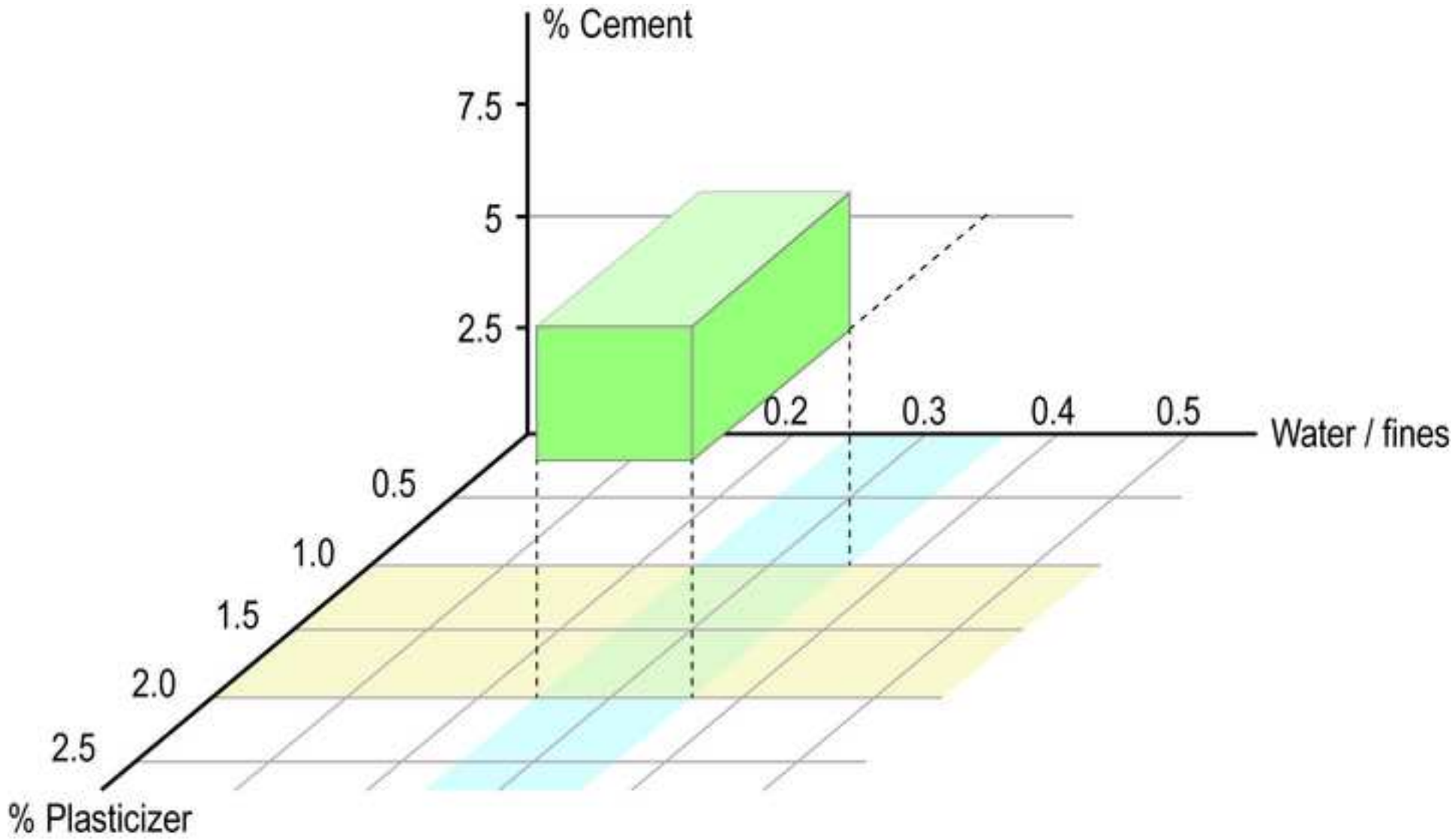
This research was conducted at the Chair of Sustainable Construction at the Swiss Federal Institute of Technology (ETH Zurich) when I was a postdoctoral fellow. It allowed Professor Habert to receive a grant from the Swiss National Science Foundation for a doctoral student. The proof-of-concept includes tests from the fresh state to the solid state. Cement was mixed with aggregates containing clay. SCCC has many foreseeable applications as an eco-building material, with a lower carbon footprint, in both developed and in-development countries. In fact, cement has a larger potential market in areas where conventional aggregates may not be available. This research aimed to enhance the research on earth construction to widen its applicability.

We hope that this manuscript will meet your expectations and those of the reviewers.

Yours faithfully,

Claudiane Ouellet-Plamondon

Graphical Abstract (for review)



Highlights

- Self-compacting clay concrete using a superplasticizer and CSA cement
- Optimization of the strength with low cement and water content
- Improved stabilized soil

Figure

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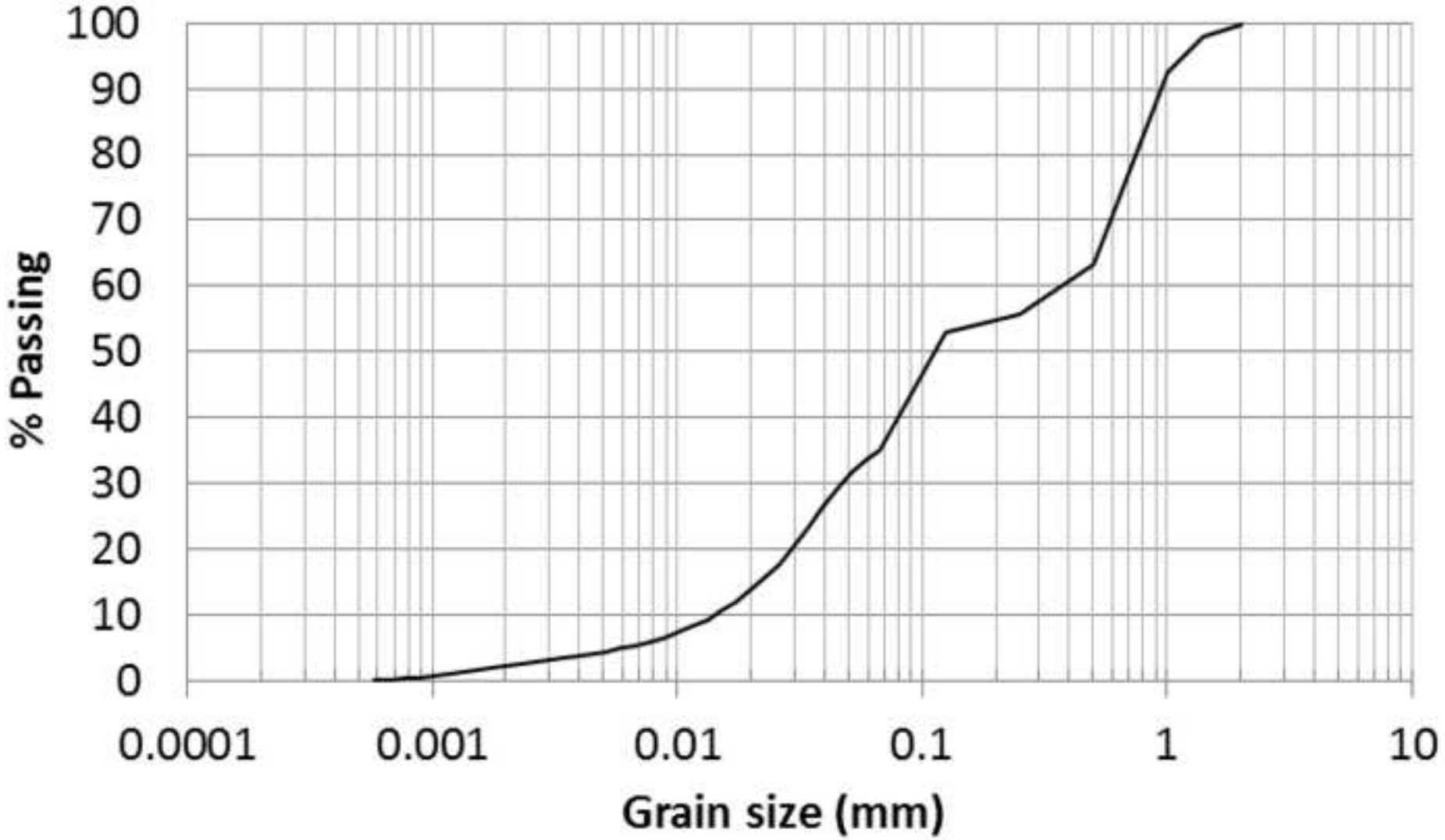

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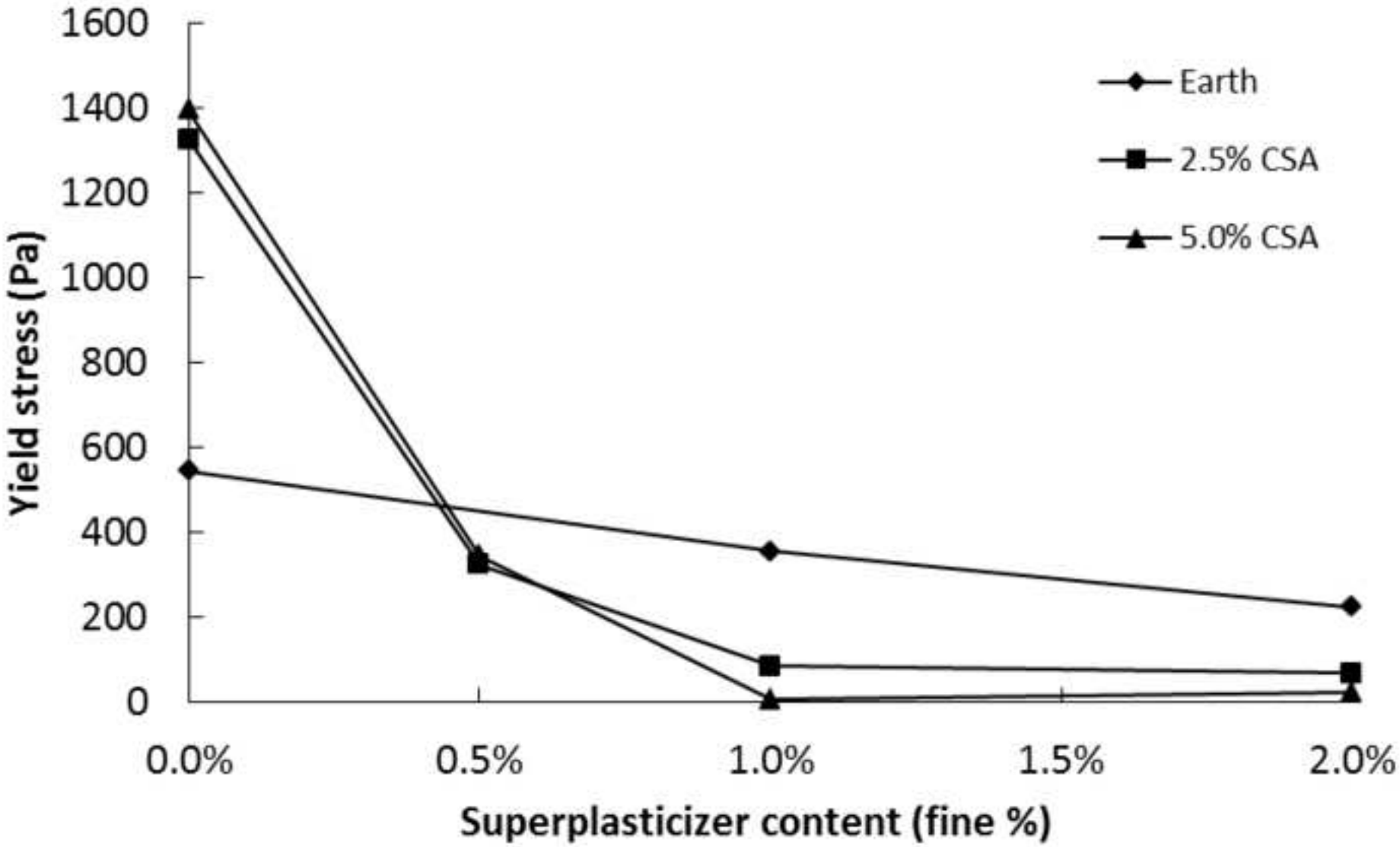

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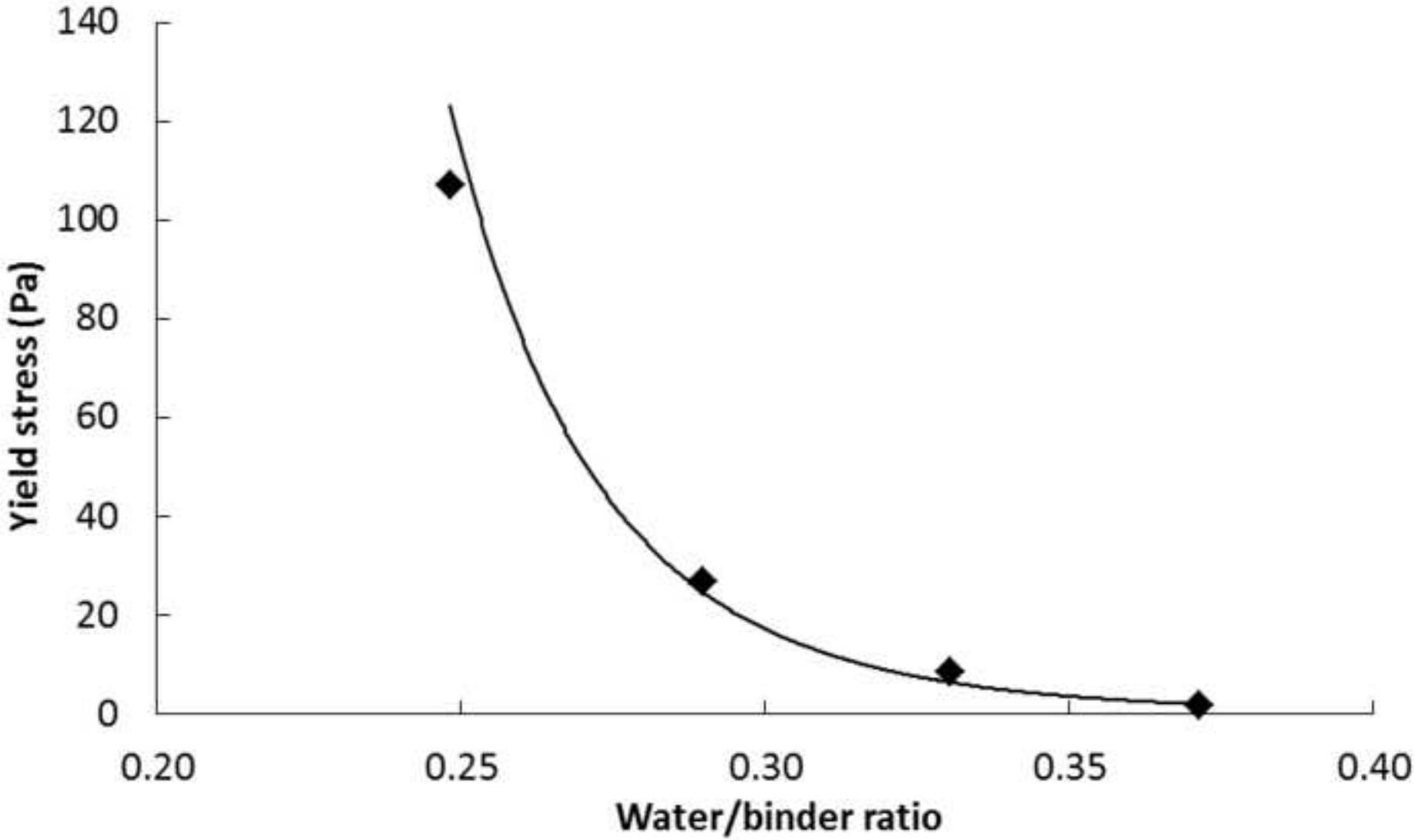

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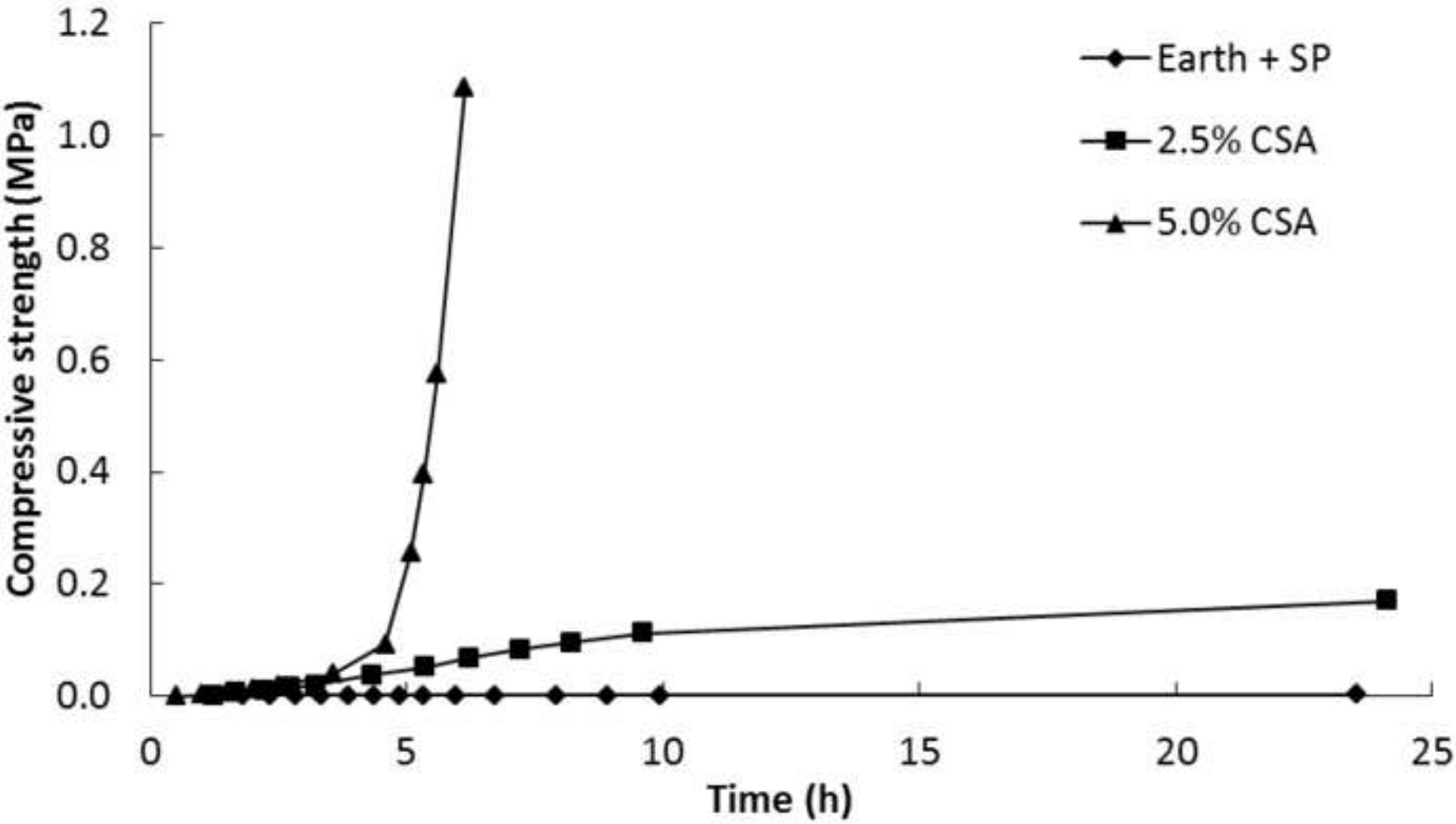

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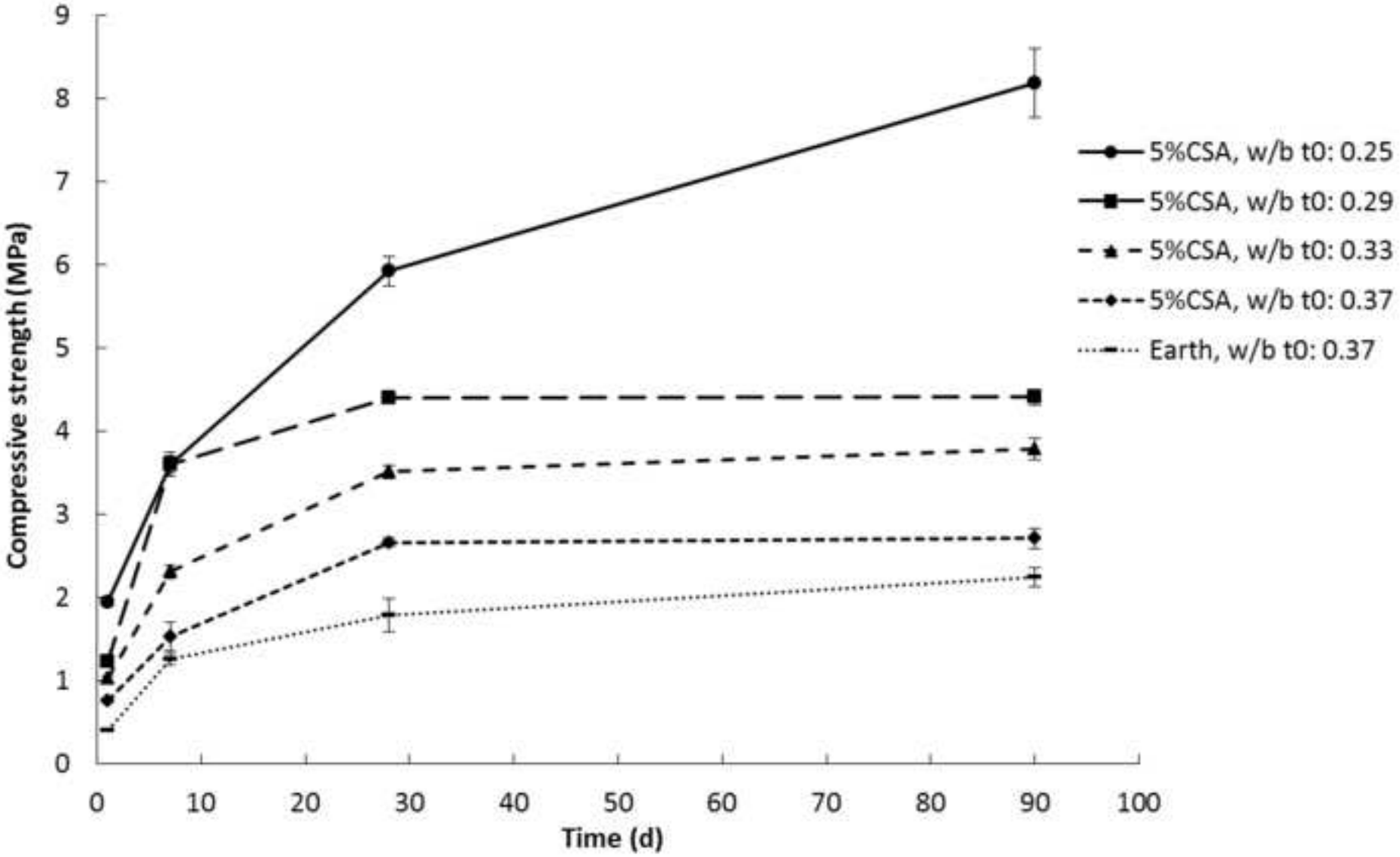

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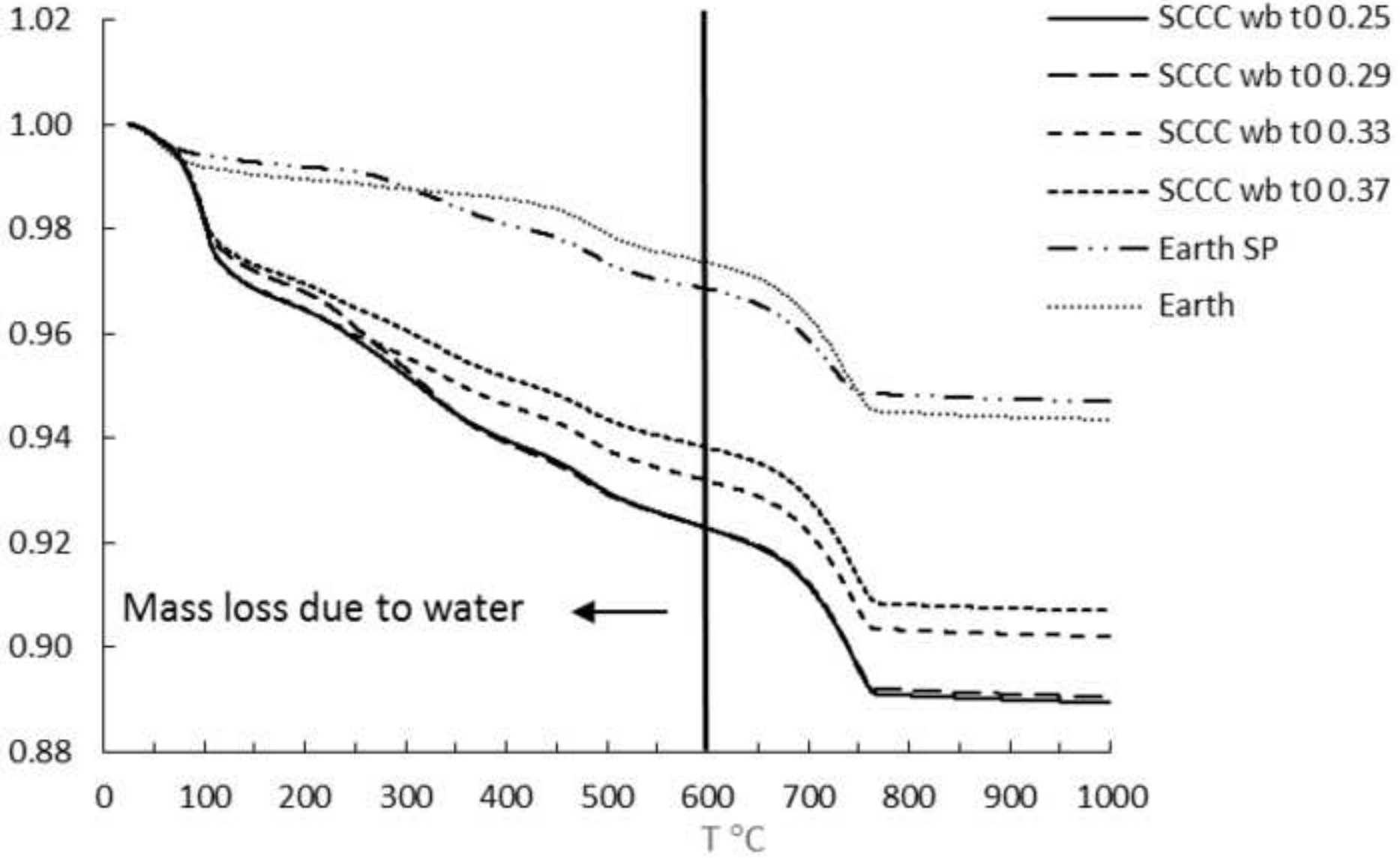

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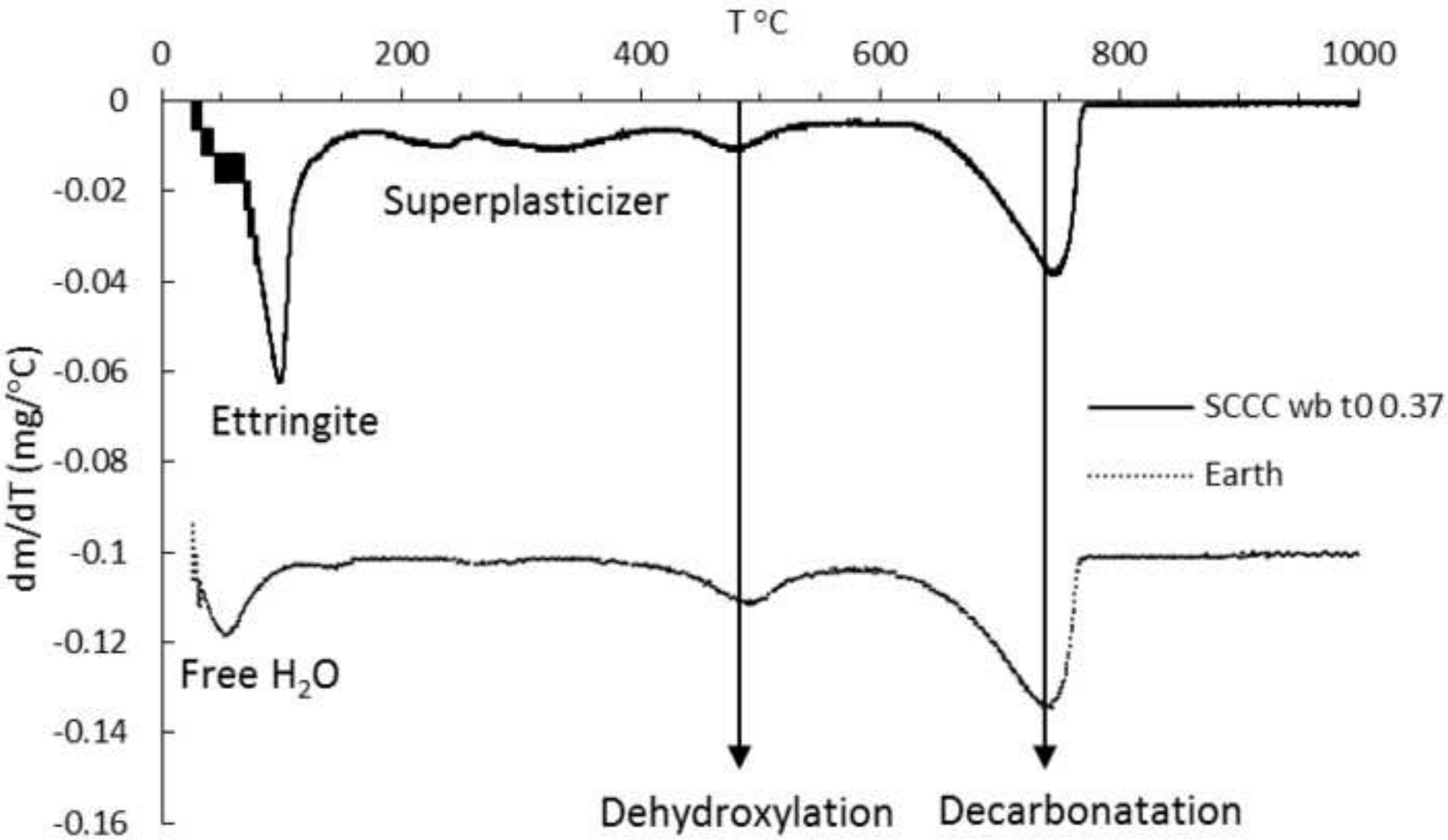

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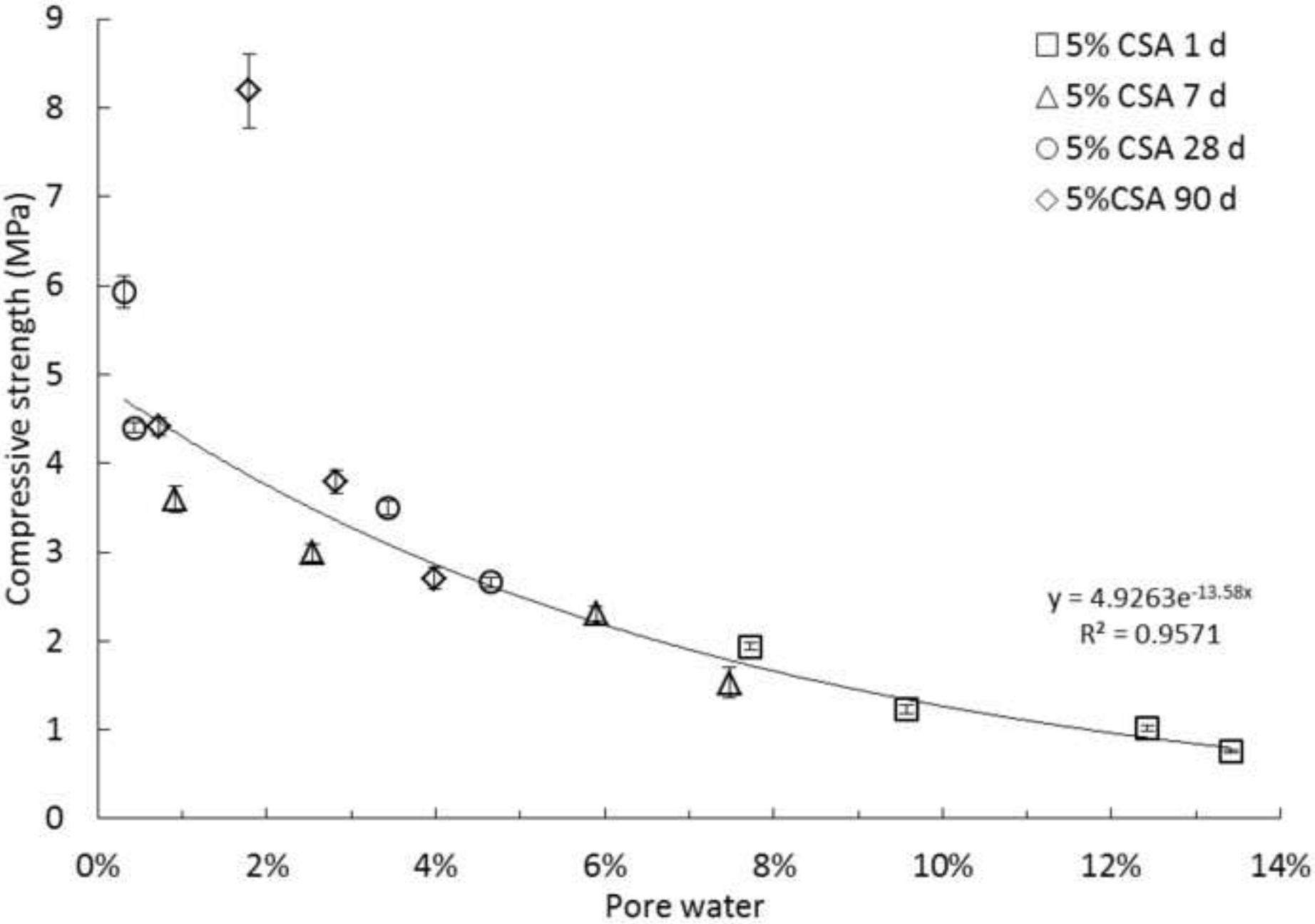

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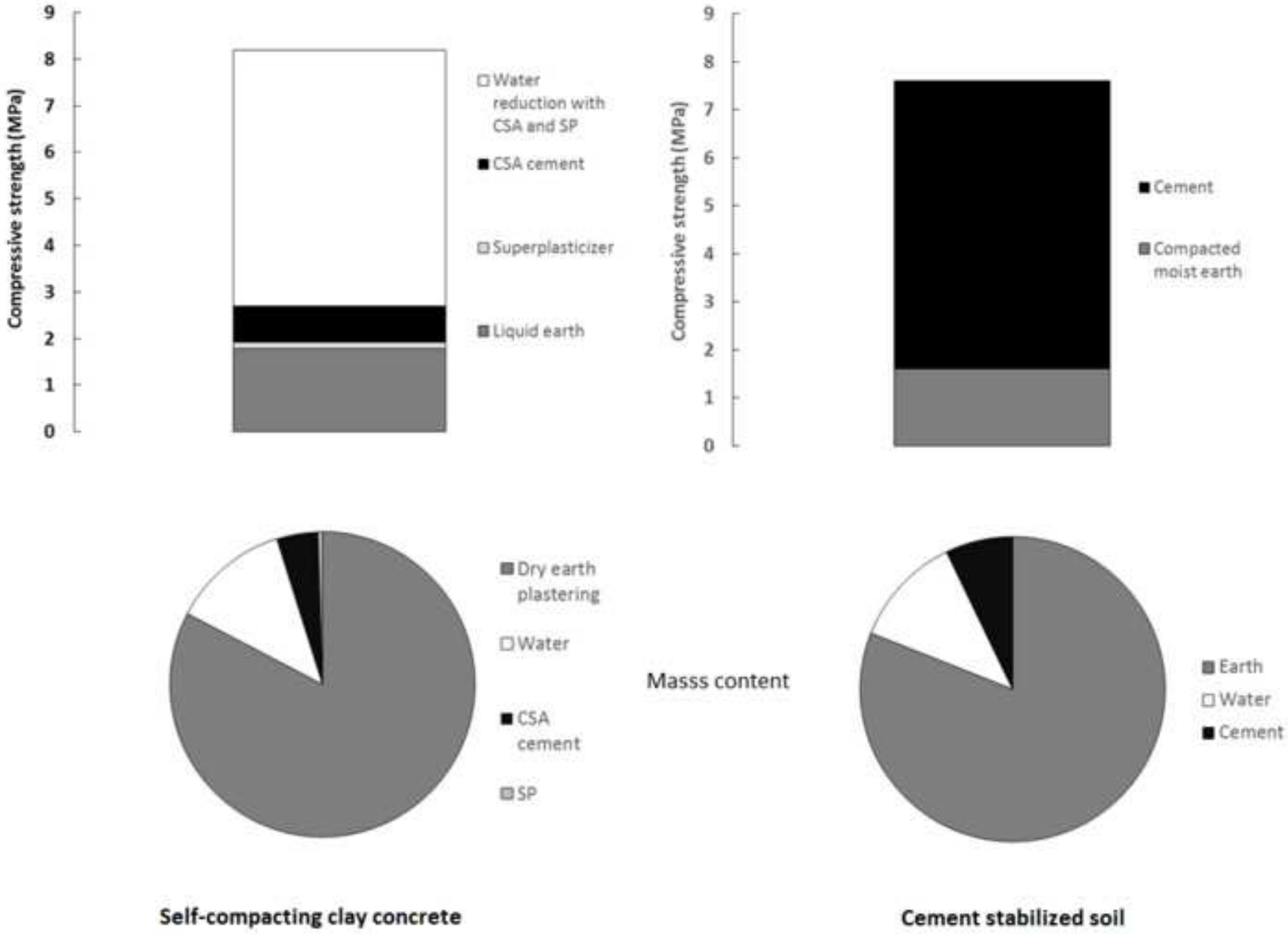

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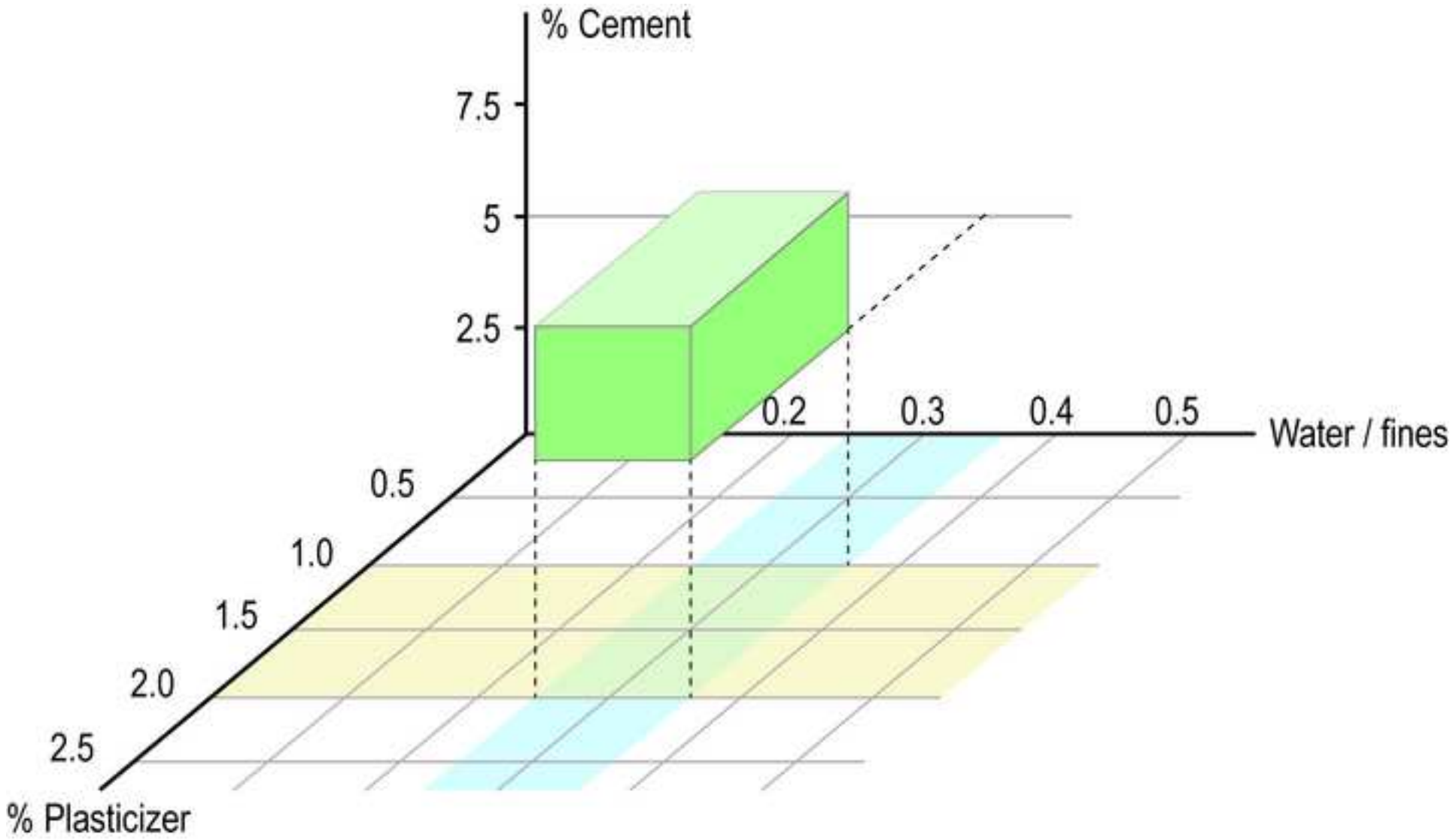

Table

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

	Functional Unit = 1 m^2 wall			
	Concrete block technology		Self-Compacting Clay Concrete	
	Mass	**Impact**	**Mass**	**Impact**
	kg	kg CO_2 eq.	kg	kg CO_2 eq.
Cement	20.8	14.6	14	9.8
Chemical admixture	0.4	0.3	5.4	4.1
Earth mortar			350	1.1
Aggregate (sand & gravel)	196.6	0.6	200	0.6
Water	10.8	0.0	65	0.0
		15.5		15.6