ADDITION OF BIO BASED REINFORCEMENT TO IMPROVE WORKABILITY, MECHANICAL PROPERTIES AND WATER RESISTANCE OF EARTH-BASED MATERIALS

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Abstract

Large amounts of natural materials are used all around the world to stabilize, to protect from water or to enhance mechanical properties of earth-based building materials. Of these materials are; alginate, tannins, oak seed extract, cellulosic glue, natural fibers washing water, casein, linseed oil and citric acid. These additions induce different mechanisms at the microstructural scale of earth-based materials and have an influence on their rheology, water sensitivity or mechanical properties. This study will focus on 4 kinds of fine soils that come from the same region (Brittany) and are composed of different varieties of clay and different contents of sand, silt and clay.

The influence of the natural additions on the rheological properties of 4 types of soil will be determined using the penetration cone test (Atterberg limits). It will be compared to the obtained results with the addition of Sodium-hexametaphosphate that acts as a strong dispersant for clay particles. Then the effect of these additions on mechanical strength in the dry state will be highlighted, especially for soils that are made of low specific surface's clay (such as kaolinite). The influence of the amount of water on the mechanical strength of the earth-based sample will also be determined for each addition. Finally a water absorption test on different dry samples of earth combined with these natural additions will be assessed to show their capacities to enhance the water durability of earth-based materials.

This study shows that natural additions, combined with contained process methods, can be a good alternative to hydraulic binders in order to stabilize earth-based building materials.

Keywords:

Earth-based materials; natural additions; rheology; water durability; mechanical strength

1 INTRODUCTION

In a context of uncontrolled global warming it is really important to improve our construction methods and to make them less impacting for the environment. Therefore raw earth is regaining consideration as a construction material due to its local character, its low environmental impact, and its high recyclability [Azeredo et al. 2008; Bui et al. 2009; Moevus et al. 2015; Aubert et al. 2016].

However raw earth is very water-sensitive, and leading to a wide range of mechanical strengths [Jaquin et al, 2009; Bui et al. 2014]. Today there is not a lot of solutions to achieve compliance with modern standards regarding strength and water durability for raw earth blocks. The common option is to add hydraulic binder to shorten the hardening of the material and to ensure a minimum strength and a water durability [Walker and Stace 1997; Venkatarama Reddy et al. 2011a; Venkatarama Reddy et al. 2011b; Khelifi et al. 2013; Tripura and Singh 2014; Landrou et al. 2014; Khelifi et al. 2015]. Another option that arises from concrete mix design, is to improve the workability of the material by deflocculating the clay particles microstructure, and thus reducing the interaction force between the clay particles [Landrou et al. 2014; Moevus et al. 2015]. Deflocculation can be obtained by using a dispersant as the Sodium-hexametaphosphate (Na-HMP) that acts like a superplasticizer on cement particles in concrete [Perrot et al. 2012; Perrot et al. 2016]. This option, for a given processing method, allows to reduce the initial amount of water, reduce the final porosity of the material and thereby improve the strength of the material and its durability.

However the use of hydraulic binders means that the production of raw earth blocks will also release a significant amount of embodied energy. Furthermore Na-HMP is a chemical product that could have a significant impact on the environment if used at a wider scale too. These additions, that are improving the material's properties, could also have an impact on the environment. Even if this impact is limited, some bio-based additions, commonly named biopolymers, could replace those products and could help to design a product with the smallest environmental impact.

Indeed a lot of natural materials are empirically used around the world to reinforce raw earth. Some previous studies already listed a lot of empirically bio-based used solutions (biopolymers) to improve raw earth buildings properties [Vissac et al. 2013, Vissac et al. 2017]. And several studies have already highlighted results on the use of those bio-based additions to enhance the strength, durability or workability of raw earth based materials and tried to explain the different mechanisms involved in these improving processes [Achenza and Fenu 2006; Galán-Marín et al. 2010; Anger 2011; Vissac et al. 2013; Dove et al. 2016; S. Hafshejani et al. 2016; Banakinao et al. 2016; Menasria et al. 2017b; Nakamatsu et al. 2017; Pinel 2017; Perrot et al. 2018]

In this study we will try to understand how several bio based additions are improving raw earth properties at different scales and for different aspects with different mechanisms. The bio-based additions that have been chosen are the following: alginate, tannins, oak seed extract, cellulosic glue, natural fibers (hay and straw) washing water, casein, linseed oil and citric acid. These bio-based additions have been selected following the different data highlighted by the previously cited papers.

2 MATERIALS AND METHODS

2.1 Four different kinds of local soils

Kaolin clay based soil

This first kind of soil has already been studied in previous works [Menasria et al. 2017a; Menasria et al. 2017b; Perrot et al. 2018]. This soil is designed with kaolin clay and fine and coarse sand. The mix is composed by mass of 17% of kaolin clay, 23% of fine sand and 60% of coarse sand. The optimized particle size distribution (PSD) of this mix is plotted in Fig. 1.

Local soil extracted in Redon, Brittany (rammed earth)

The second material that has been tested is a rammed earth from Redon (Brittany). It is a fine loam soil with only 5% of particles finer than 10 µm and 97% of particles finer than 2 mm. The soil particles are a mix of quartz and various types of clay: kaolinite, illite and chlorite, determined by XRD analysis. The Plasticity Index of the soil is about 14.5 with a liquid limit of 36.5% and a plastic limit of 22%. The PSD of this soil has been obtained by laser diffraction and sieving (Fig.1).

Local soil extracted in Bréal-sous-Monfort, Brittany.

The third material that has been tested is a soil from Bréal-sous-Monfort (Brittany, France). It is a fine clayey and silty soil .The soil particles are a mix of quartz and various types of clay: kaolinite and illite. The Plasticity Index of the soil is about 15.5 with a liquid limit of 35.7% and a plastic limit of 20.2%.

Local soil extracted in St Sulpice, Brittany (cob earth).

The fourth material that has been tested is a cob earth from Saint-Sulpice-La-Forêt (Brittany, France) and has already been used in previous studies [Menasria et al. 2017b; Perrot et al. 2018]. It is a fine soil with 70% of particles finer than 10 µm. The soil particles are a mix of quartz and various types of clay: kaolinite, illite and some traces of smectite (swelling clay). These swelling clays couldn't be found on all of the samples but this soil has been mixed up and homogenized before the experiments so it is very likely that there is a small amount of smectite in each of the sample that has been tested in this study. The Plasticity Index of the soil is about 16.5 with a liquid limit of 46% and a plastic limit of 29.5%. The PSD of this soil is plotted on Fig. 1.

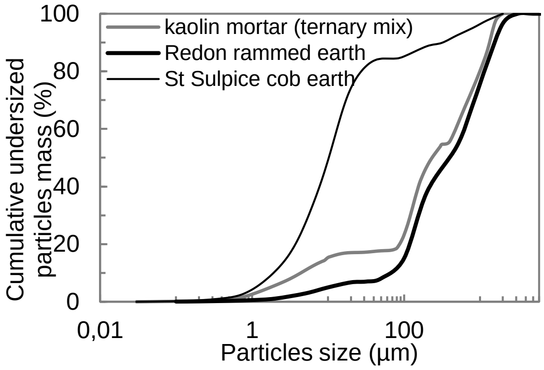

Fig. 24: Particle size distribution of studied soils

2.2 Bio-based additions, their potential induced mechanism to reinforce raw earth materials

As stated previously, several bio based additions have been tested after a review of previous studies and traditional recipes: alginate, tannins, oak seed extract, cellulosic glue, natural fibers (hay and straw) washing water, casein, linseed oil and citric acid. These additions have been selected because they can easily be found in Brittany for a potential local production of raw earth blocks. These additions and their potential induced mechanisms are described in the following subsections.

Casein (Cas)

This molecule has both hydrophilic and hydrophobic properties. Casein is used in traditional earth construction as a reinforcement regarding water durability, as a coating or mixed up in the mass of the material [Vissac et al. 2013, Vissac et al. 2017]. In Brittany, the dairy industry is quite expanded and some casein could be extracted from industrial wastes (out of date milk) and be reused as a bio-based stabilizer for raw earth construction at a larger scale. In this study micellar casein powder of the trademark "Bulk Powders" will be used. Different tests have been performed to determine the optimum dosage in casein. Regarding the Fig. 2 that shows the methodology used to find the best dosage for a given soil, the optimum dosage retained for the addition of casein powder is 5% of the mass of the fine part of each soil (clayey part).

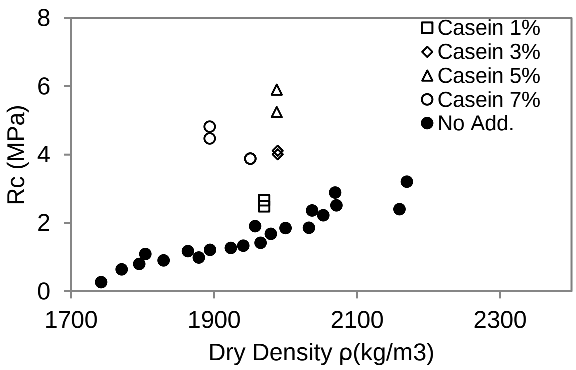

Fig. 25: Methodology to highlight the best dosage in casein to enhance the compressive strength of the kaolin material at dry state

Alginates (Alg)

A solution is to use a gelling agent such as alginate to strengthen and allow a fast demolding of a cast earth-based material. Alginates are a family of seaweed biopolymers that are alginic salts emerged from the cells of brown seaweed. The chains of alginate can attach themselves by intercalating divalent cations such as

Ca^{2+} (which can be found in earth based materials or in calcium ions release agents) and thus form a cross-linked isotropic insoluble gel [Funami et al. 2009]. Alginates have already been tested in previous studies as a stabilizer for raw earth material [Achenza and Fenu 2006; Galán-Marín et al. 2010; Dove et al. 2016; Menasria et al. 2017b; Perrot et al. 2018].

In this study, the used alginate is a white powder of alginic salt Cimalgin HS3® provided by Cimaprem (Redon, France). This powder has already been used in [Menasria et al. 2017b; Perrot et al. 2018] works. The dosage retained here will be 3% in mass of fine part of the soil.

Cellulosic Glue (CG)

Vegetal cellulosic glue addition will also be tested in this study. According to [Vissac et al. 2017], a lot of different vegetal glues are used all around the world to enhance the properties of earthen constructions. In this study, an industrial 100% vegetal wallpaper glue will be used with a dosage of 6.25 grams per litre of mixing water.

Hay and straw washing water (HWW and SWW)

In vernacular raw earth construction, the addition of fermented vegetal fibres [Vissac et al. 2017] is also a usual practice to stabilise the earth coatings. To check if the fermentation of these fibres has a role in the strengthening of raw earth, in this study washing water of fermented fibres (hay and straw) have been add as mixing water for some samples. To achieve these mixing liquids, 500 grams of fibres have fermented in 10 litres of water during 1 month.

Linseed Oil (LO)

According to [Vissac et al. 2013, Vissac et al. 2017] statements, linseed oil has been used in earthen construction in France in order to improve earth material water durability as a coating. Linseed oil (LO) is a siccative oil that polymerize and oxidize during its slow drying. After this drying the fatty acids are strongly bonded together and are protecting the raw earth material from water by dint of their hydrophobic properties. For the experiments ¼ of the addition of mixing liquid will be LO and the other ¾ will be water.

Citric Acid solutions (Citr. Ac. pH2 and Citr. Ac. pH4)

Clay particles are very sensitive to pH variations [Anger 2011]. The apparent workability of a raw earth material at a given water content can vary form a plastic state to a liquid state with only a change of pH conditions. In this study, two different citric acid solutions (at two different pH values, pH=2 and pH=4) will be tested in order to understand how they can act as dispersant such as Na-HMP [Perrot et al. 2016].

Tannins (Tan)

In raw earth traditional construction, tannins are also used to provide water durability and strength to earthen walls [Banakinao et al. 2016; Vissac et al. 2017]. Some others studies have highlighted that under certain conditions, tannins could also act as dispersant for clay particles [Anger 2011; Vissac et al. 2013].

In this study the tannins that are used are chestnut tree tannins, usually used for grapes vinification in inox-tanks. The dosage retained here will be 2% or 4% in mass of fine part of the soil.

Oak Seed extract

[Samadzadeh Hafshejani et al. 2016] highlighted the fact that an Oak Seed Extract (OSE) could be used as a dispersant for bentonite drilling mud. In this study the addition of an oak seed extract through various forms will be assessed in order to highlight its likely dispersive properties for raw earth based materials. The first form is an OSE powder sieved at 315 μm, the other form is a water based solution of this powder with a powder content of 75 grams per litre. In the case of the addition of OSE powder, the dosage will be 4% in mass of fine part of the soil.

Sodium-Hexametaphosphate (HMP)

In order to compare the bio-based dispersants to a reference product known as an efficient dispersant, Hexametaphosphate (HMP) will be used as it is used in previous studies [Perrot et al. 2016]. 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 behaviour of clay pastes.

Vegetal based varnish

For the absorption tests part, a bio-based varnish without volatile organic compounds and Formaldehyde, made of vegetal oils emulsion will be used. It is a varnish of the trademark “Nature et Harmonie”.

2.3 Experimental methods

These several bio based additions have different effects on the raw earth material properties. First they can increase significantly the compressive strength of the material, they can also improve its water durability by protecting the bonds between the clay particles. Finally they can act as dispersants and thus improve the workability of the material. A dispersant allows to reduce the initial amount of water, reduce the final porosity of the material and thereby improve the strength of the material and its durability.

Different experimental tests have been performed to highlight those different effects.

SEM Observations

First of all, some kaolin based samples with bio-based additions at a high dosage have been carried out and examined with scanning electron microscope (SEM). This microscope allows to get high-resolution images of the samples and to analyze the visible effects of some of the bio-based additions. It also allows to get information on the chemical composition of the samples.

pH measurements

Some previous studies have highlighted the fact that clay particles are very sensitive to pH variations [Anger 2011]. The apparent workability of a raw earth material at a given water content can vary form a plastic state to a liquid state with only a change of pH conditions. Some of the additions tested in this paper can act as dispersants, and following the pH variation of the interstitial water with different additions could give some clues regarding the mechanisms induced in the dispersion of clay particles.

Geotechnical tests: Atterberg limits of different soil mix

Some of the additions can act as dispersants, and some of them can rather act as a colloidal agent. Some simple tests, at a bigger scale than the previous depicted experiments, can give information on the dispersing or flocculating properties of the tested additions.

To characterize the consistency of a soil at a certain water content, its apparent shear behaviour can be measured. As in [Perrot et al. 2016] study, some geotechnical tests will be carried out to characterize the rheological behaviour of different mixes of soils with several bio-based additions. The aim is here to estimate the workability of the different studied pastes from the measurement of plastic limits of clay. These plastic limits (Atterberg limits) are critical water contents that allow the determination of a plasticity index Ip (difference between plastic limit w_p and liquid limit w_l) which indicates the range of water content where the soil behaves as a plastic material. The liquid limit will be determined using the fall cone method following the French national standard recommendation NF P94-052-1 (AFNOR). The plastic limit will be determined following NF P94-051 (AFNOR).

For a given soil, the evolution of these limits after the addition of bio-based additions will give clues on whether or not those additions are acting as dispersants.

Absorption tests

According to [Vissac et al. 2013, Vissac et al. 2017] some of those additions have properties to decrease the water sensibility of raw earth based materials. In order to highlight this kind of effect, a capillary absorption test has been developed, inspired by French national standard recommendation NF EN 13057 (AFNOR) and the capillary absorption test of French national standard recommendation XP P 13-901 (AFNOR) for cement stabilized compressed earth blocks.

Earth-based cast 20*40*40mm^3 samples, mixed with different bio-based additions have been placed on filter paper and a nylon grid, on a water soaked sponge, in a flush water bath. The sample weight change versus the experiment duration has been followed. A capillary absorption coefficient (A_{cap}) could thus be fixed. The comparison of the different A_{cap} values for several mix of raw earth material should give information on the decreasing water sensibility properties of some bio-based additions.

Compressive strength evolution with water content

The compressive strength of earthen material is widely decreasing with the increase of its water content. Indeed [Bui et al. 2014] have shown that the compressive strength of a raw earth sample is divided by 4 when the water content was varying from 2% to 10%. [Jaquin et al. 2009] explained that this variability is due to the suction effects linked to the capillary forces induced by the drying of the material. Regarding this physical phenomenon and the initial compressive strength of the earthen material, the bio-based additions could have two different roles. Firstly they could increase the compressive strength of the material at the dry state [Menasria et al 2017b; Perrot et al. 2018] and then they could limit the decrease of mechanical strength while the water content of the material is increasing. Thus, the compressive strength evolution with water content has been measured for several mix of raw earth material. All of the mix have been casted in cement mortar 40*40*160 mm^3 moulds. All the compressive tests have been carried out with sample of an aspect ratio of one in agreement with the French national standard recommendation for mechanical strength measurements on mortars NF EN 196-1 (AFNOR).

3 IMPACTS OF THE BIO-BASED ADDITIONS ON THE RHEOLOGICAL BEHAVIOUR OF RAW EARTH MATERIALS

One of the expected effects of the bio-based additions experimented in this paper, is to act as dispersants. In the following subsections, quite a few experiments try to highlight from different angles the action mechanisms of the addition of bio based products to earth based materials and compare it to the achieved results for an already known efficient dispersant (HMP) and for the soil without any addition.

3.1 SEM Observations

First of all, kaolin-mortar based samples with different additions at a high dosage have been carried out and examined with scanning electron microscope (SEM). Some of the tested additions are supposed to act as dispersants, and with the SEM high resolution images these effects can be noticed.

According to [Perrot et al. 2016], without any dispersant the kaolin particles network is in a house of cards configuration. Kaolin particles have negatively charged faces and positively charged edges. Without addition the edges are attracted to the faces of other kaolin particles. By adding a dispersant as Na-HMP, the edges of each particles become uncharged and the organisation of the clay particles is changing from a house of cards configuration to an organisation where the kaolin particles are becoming aligned.

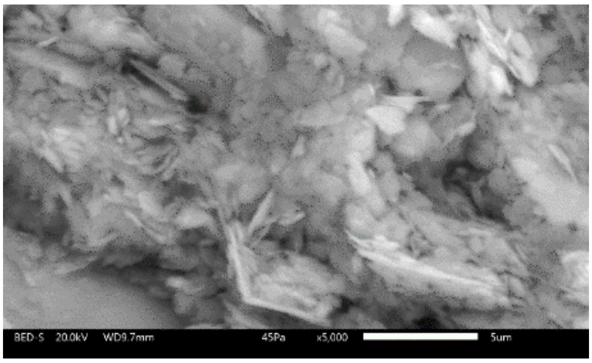

Fig. 26: SEM observation of dry cast kaolin based material

Fig. 3 shows the configuration of the particles network of a kaolin-based mortar without any addition at the dry state. The “house of cards configuration” is clearly visible on this picture, the kaolin particles are oriented in plenty of different directions, and the network organisation does not seem optimized.

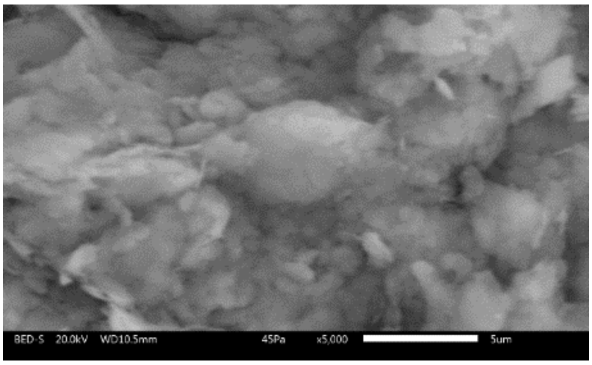

Fig. 27: SEM observation of dry cast kaolin based material mixed up with Na-HMP

Fig. 4 shows the configuration of the particles network of a kaolin-based mortar mixed up with Na-HMP addition at the dry state. The “lined-up configuration” is also clearly visible on this picture, the kaolin particles are oriented in the same direction, linked to the sand and silt grains, the network organisation seems optimized. The dispersant effect is clearly highlight by this picture.

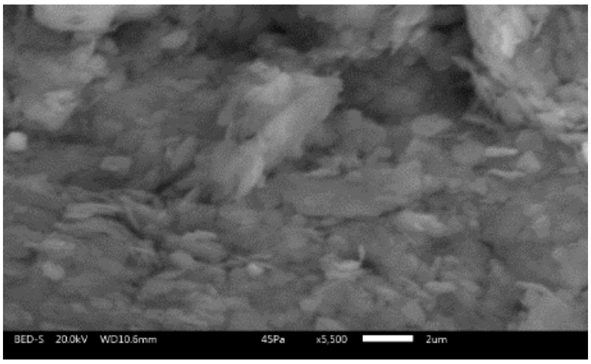

Fig. 28: SEM observation of dry cast kaolin based material mixed up with Citric acid solution at pH2

Fig. 5 highlights the configuration of the particles network of a kaolin-based mortar mixed up with citric acid solution at pH2 at the dry state. This configuration seems to be in between the two previously cited configurations. Kaolin clay particles seems to have a main direction and to be lined up, but some of them seems to still be in a “house of cards” configuration. Similar configuration has been noticed for the addition of tannins, and, at a lower scale, for the addition of OSE and citric acid solution at pH4. For the others bio-based additions, the “house of cards” configuration is still visible.

Following these observations, citric acid, tannins and OSE seems to act as dispersants, but with a lower effect than Na-HMP which is known as an efficient dispersant for clay particles.

3.2 pH measurement

As stated previously, some studies have highlighted the fact that clay particles are very sensitive to pH variations [Anger 2011] and that the consistency state of a raw earth mortar can vary form a plastic state to a liquid state with only a change of pH conditions. Following the SEM observations that have led to the conclusion that some of the bio-based additions (Citric acid, tannins and OSE) could act as dispersants, the pH value of the interstitial water of different mix of different soils has been measured. Tab. 1 is listing the results of this experiment.

Tab. 13: pH Value of the interstitial water of different mix of different soils

Mix	**pH value of the interstitial liquid**		
	Kaolin	**Redon**	**St-Sulpice**
Soil	7.7	7.5	7.1
Soil+HMP	4.3	5.4	6.0
Soil+tan (4%)	4.2	3.9	3.8
Soil+OSE (4%)	7.2	5.1	6.9
Soil+Citr. Ac pH4	5.1	7.1	5.7
Soil+Citr. Ac pH2	2.6	2.5	2.7

First of all, regarding the pH value change after the admixture with different bio-based additions, each soil seems to react similarly to the addition of each product. As expected the addition of citric acid solution at pH2 leads to the lowest pH value for each soil. In this case the change of pH seems to be the mechanism that leads to a dispersion of the clay particles.

For the addition of tannins, the change of pH value is also substantial and could be one of the reason of the induced clay particles dispersion. However according to [Anger 2011; Pinel 2017] tannins are organic acids that are mainly acting as complexing multivalent anions. They can be adsorbed on the edges of the clay particles and thus act as dispersant of the clay network. In this case, the chemical induced phenomenon is the electrostatic repulsion. The efficiency of this addition is varying with the pH of the chemical environment. Some additional experiments as adding simultaneously pH2 citric acid and tannins to a soil mortar could be interesting in order to have symbiotic dispersing properties of citric acid and tannins.

Then, the addition of other bio-based products is also leading to changes of pH value but at a lower scale. For HMP addition, the change of the pH value is not the mechanism that leads to the clay particles dispersion since the addition of Na-HMP in raw earth material is inducing an electrostatic repulsion between the particles.

3.3 Geotechnical tests: plastic and liquid limits of different soil mix, rheology measurements

As stated before, some of the additions can act as dispersants, and some of them can rather act as a colloidal agent. Some simple tests, at a bigger scale than the previous depicted experiments, can give information on the dispersing or flocculating properties of the tested additions. This is the reason why a campaign of geotechnical tests to determine Atterberg limits (plastic limit and liquid limit) of a wide range of different soil mix has been achieved. The results are plotted in Tab.2. The addition of dispersant is reducing the both liquid and plastic limits (green characters in Tab.2) while the addition of a colloidal agent is increasing these limits (red characters).

As expected, the lowest plastic and liquid values (W_p and W_l) are obtained for each sort of soil for the Na-HMP addition which is the strongest dispersant tested here. However, according to Tab. 2 citric acid, tannins and OSE powder seems to act as dispersants at a lower scale for all of the four sorts of soil. These bio-based additions can help to improve the rheology of raw earth based materials and thus increase their dry density and other mechanical properties.

Some bio-based additions as OSE solution and Hay and straw washing waters do not seem to have any effect on the rheology of the earth based materials tested.

Finally, others organic additions as casein, alginates and cellulosic glue are acting as colloidal agents for all sorts of soil. For this kind of addition the initial amount of water to carry out an earth block will have to be increased, and thus this earth block will risk to have a lower density, and higher shrinkage. However, the solution to optimize the density of the material with this kind of addition is to add some Na-HMP at the admixture.

Tab. 14: Geotechnical tests: plastic and liquid limits of different soil mix, rheology measurements

Consistency Limits values								
Mix	Kaolin		Redon		Bréal		Saint-Sulpice	
	Wl(%)	Wp (%)	Wl(%)	Wp (%)	Wl(%)	Wp (%)	Wl(%)	Wp (%)
Soil	**65.5**	**31.3**	**36.5**	**21.8**	**35.7**	**20.2**	**46.2**	**29.7**
Soil+HMP	**45.1**	**27.5**	**22.2**	**18.1**	**26.1**	**18.9**	**33.3**	**21.7**
Soil+tan (4%)	**59.5**	**30.3**	**27.8**	**15.5**	**31.1**	**18.4**	**38.1**	**23.9**
Soil+Citr. Ac pH2	**57.1**	**25.8**	**30.3**	**16.7**	**-**	**18.3**	**42.3**	**21.9**
Soil+Citr. Ac pH4	**60.3**	**29.8**	**34.7**	**18.0**	**-**	**18.8**	45.7	**23.6**
Soil+OSE powd. (4%)	**59.6**	**30.2**	**32.7**	**23.5**	**32.7**	**21.7**	45.2	**26.9**
Soil+OSE Solution	**62.4**	30.8	**44.2**	21.0	35.2	**21.9**	**49.6**	**25.0**
Soil+HWW	61.6	**33.6**	35.4	22.6	34.1	18.1	45.0	**26.5**
Soil+SWW	66.4	32.4	36.4	23.0	34.4	**21.5**	46.1	27.9
Soil+Cas	**84.7**	**34.4**	**54.5**	**31.3**	**54.9**	**30.4**	**60.6**	**34.1**
Soil +CG	**71.8**	**32.5**	**40.3**	21.3	**41.3**	**23.7**	**54.5**	**30.2**
Soil+Alg.	62.7	**33.5**	36.4	**24.3**	**38.9**	**23.2**	**51.9**	28.7
Soil+LO	*53.8*	-	*27.6*	*18.1*	*30.3*	*16.5*	*35.2*	*23.7*

For the addition of Linseed Oil, the results are probably inaccurate since the viscosity of the oil is different of the water viscosity, and the fall cone method is designed for soil mixed up with water. Nevertheless, preliminary extrusion tests carried out in the lab have shown that addition of linseed oil requires an increase in the water content in order to obtain similar flow characteristics.

As stated previously it could be Interesting to add simultaneously pH2 citric acid and tannins in a mix to try to improve and measure their dispersing properties and maybe create a bio-based equivalent of Na-HMP.

4 IMPACTS OF THE BIO-BASED ADDITIONS ON THE WATER ABSORPTION OF RAW EARTH MATERIALS

According to [Vissac et al. 2013, Vissac et al. 2017] some of those additions have properties to decrease the water sensibility of raw earth based materials. To measure and qualify these properties, a capillary absorption test has been developed inspired by capillary absorption tests for cement mortars and earth bricks in French national standards. From these absorption tests we can obtain the following shape of curve (plotted in Fig.6) that highlights the amount of absorbed water by capillarity for a given surface of material function of time.

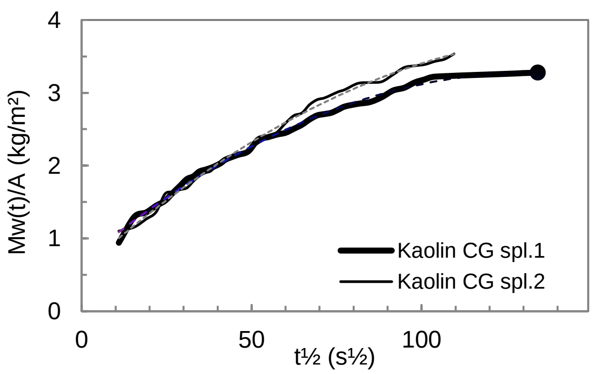

Fig. 29: Absorption curve of a dry kaolin mortar mixed up with hmp and cellulosic glue

According to Hall's method, validated by [Feng and Janssen 2018], a capillary absorption coefficient can be extracted from this sort of representation, with the following equation:

$$\frac{m_{wet} - m_{dry}}{A} = A_{cap} \times t^{0,5} + k_1 - k_2 \times t$$

For three different soils, and for different bio-based additions all combined with HMP, several A_{Cap} values have been determined on 20*40*40 mm^3 cast samples. In order to pull away the effect of the different porosities of the samples, all of the A_{cap} values have been divided by the apparent porosity n of the sample:

$$n = 1 - \frac{\gamma_d}{\gamma_s} \; with \; \gamma_s = 26kN/m^3$$

The obtained values are plotted in Fig.7.

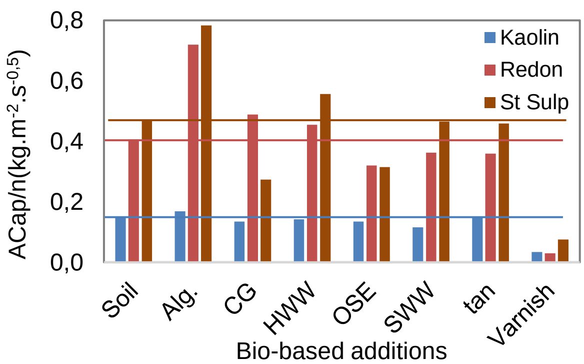

Fig. 30: Values of A_{cap}/n for different bio-based additions

First of all, it is clear on this chart that the different soils have different potential of capillary absorption levels. It is surely induced by the different sort of clays that are composing the fine part of each soil and by the size of this clayey part compared with the sanded and silted parts (different pore structures).

Then, for almost all of the additions tested in this experiment, their effect on the capillary absorption is not major. In some cases, OSE, Tannins, fibres washing waters and Cellulosic glue can slow down the absorption rate. For each sort of soil, alginates seem to increase the capillary absorption.

But for the natural varnish coating, the result is really interesting. The capillary absorption is strongly slowed down. It seems to be a good solution to decrease water sensitivity of earth based materials.

This absorption test still has to be performed for the other bio-based additions such as casein and linseed oil, which should have interesting properties since it is a hydrophobic vegetal oil that could reduce the water sensitivity of earth based materials. It seems important to use the less processed bio based additions and to prefer simple vegetal oil instead of processed varnish.

5 IMPACTS OF THE BIO-BASED ADDITIONS ON THE MECHANICAL STRENGTH OF RAW EARTH MATERIALS WHILE WATER CONTENT IS INCREASING

Finally, these bio-based additions could increase the compressive strength of the material at the dry state [Menasria et al 2017b; Perrot et al. 2018] and then they could limit the decrease of mechanical strength while the water content of the material is increasing. For the kaolin mortar, several additions have been studied.

For each mix, the compressive strength of the material at the dry state has been measured. The results are plotted in Tab.3.

Tab. 15: Compressive strength at the dry state and dry density of different kaolin-mortar based materials

Bio-based Addition	Kaolin	
	Dry Density (kg.m^{-3})	R_cMax (MPa)
Soil	1951	1,16
HMP	1958	1,90
Citr. Ac. pH2	1899	1,97
OSE	-	2,23
HMP+HWW	-	2,18
HMP+SWW	1978	2,19
HMP+tan	1764	2,77
HMP+Alg.	1932	2,38
HMP+Cas.	1933/1988	2,69/5,9
HMP+CG	1949	1,86
HMP+LO	1961	5,00

Some of the bio-based additions, such as citric acid, OSE, fibres washing water, and cellulosic glue do not seem to have a huge effect on the compressive strength of the material compared to the material with HMP, but OSE and citric acid can still act as dispersants. Tannins and alginates seem to slightly improve the dry compressive strength of the material. But linseed oil and casein are the bio-based additions that allow to reach the highest dry compressive strengths (5MPa for linseed oil and 5.9MPa for casein).

However, those results have to be balanced, since the dry densities of these samples are varying. This experiment should be led with a forming process that is leading to the same dry density for each sample. Then, the evolution of the compressive strength of each kaolin-mortar based mix has been followed while the water content was increasing. The results are plotted in Fig.8.

For all of the mix the same trend that is shown in [Bui et al. 2014] study is noticeable. The only addition that allows to reach an efficient compressive strength (higher than 2MPa) for a water content of 1% is the linseed oil. That is probably due to its hydrophobic properties and its drying polymerization and oxidation that strengthen the material [Vissac et al. 2013, Vissac et al. 2017].

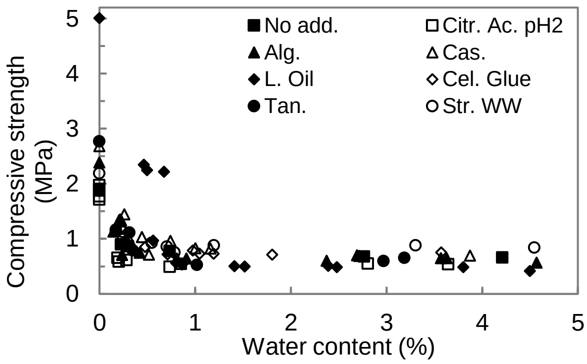

Fig. 31: Evolution of the compressive strength of several kaolin-mortar based materials with water content

6 CONCLUSIONS

This paper has shown that several bio-based solutions could help to strengthen the raw earth based materials, and provide them a better workability, reduce their water sensitivity and improve their compressive strength.

First of all, it has been proven that citric acid, tannins or oak seed extract could have dispersing properties for the clay particles and could maybe replace the Na-HMP as dispersants to easily improve regularly the density and the strength of the material, and thus help to optimize processing methods at a semi-industrial scale. But these additions are still weaker dispersants than Na-HMP. It could be interesting to add simultaneously pH2 citric acid and tannins in a mix to try to improve and measure their dispersing properties and maybe create a bio-based equivalent of Na-HMP.

Then, these bio-based additions have been tested in order to reduce the capillary absorption of raw earth based materials. Cellulosic glue seems to have a good effect but the best result has been obtained for the vegetal oil based varnish. Regarding this result, it could be interesting to achieve the same test with the addition of linseed oil that could be a good addition to reduce water sensitivity of earthen material.

Then these additions have been tested to improve the dry compressive strength of a low potential strength material (kaolin mortar). Some additions as casein, alginates, tannins and linseed oil seem to really improve these properties, but during this experiment the dry density of the mix was varying widely. Further experiments will be performed, at a fixed dry density.

Finally, these additions have been tested to protect the samples from the decrease of compressive strength due to the increase of water content of the material. The only addition that was good enough to play this role was the linseed oil.

These bio-based additions, wisely selected, combined with contained process methods, can be good alternatives to hydraulic binders and chemical dispersants in order to stabilize earth-based building materials and produce raw earth blocks that achieve compliance with modern standards regarding strength and durability.

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