POTENTIAL ORGANIC BINDERS TO STABILIZE EARTH CONSTRUCTION MATERIALS

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Abstract

The use of earth as construction material for modern buildings is a topical issue regarding the significant CO_2 emission of the construction sector. Indeed, this millenary material can be used for environmental friendly buildings thanks to its hygrothermal properties, its wide spread availability and its low CO_2 emission. However, earth materials still have to meet satisfactory mechanical strengths and water erosion resistance to satisfy the current construction standards. Therefore, most industrial applications and scientific studies used cement or lime to stabilize earth. But the high CO_2 footprint due to the high amount of the mineral binders added to these materials inhibits their sustainability. An overview of the vernacular construction techniques and the existence of ancient earth buildings revealed the use of organic binders as earth stabilizers. The organic binders are natural polymers extracted from plants or animals and mixed with earth and water generally for improving its water resistance.

This study aims to identify the stabilizing potential of some of those organic polymers. Four organic polymers have been chosen for the study: polysaccharides (wheat starch, alginic acid), and proteins (casein, egg white albumin). Specimens were prepared with two types of soils and various amounts of each organic binder. Specimens were then tested according to their mechanical strength and their resistance to water. Simple tests highlighted very promising organic binders especially the proteins while for the others, it was observed that the efficiency depended on several parameters (the mixture procedure, the type of the soil and the chemical pre-activation).

Keywords:
Earth construction materials, organic binders, mechanical strength, water resistance

1 INTRODUCTION

The global warming arose a conscientiousness of the importance to mitigate construction sector's share of the global greenhouse gas emission. The systematic use of cement based materials for all types of construction including individual housings, is one of the main cause of the construction sector related CO_2 emission. In fact, [Gartner, 2004] reported that the production of 1kg of Portland cement generates a total of 0.94 kg of CO_2 emission and this doesn't take into account the trading transport related emission. Therefore, the new trend in construction materials research area is to find out the material with a good compromise between the usage performances on one hand, and the durability and the sustainability on the other hand. Hence, unfired earth based materials seem to be a relevant alternative to concrete especially for housing buildings. Basically used as a vernacular construction material in the worldwide, earth is getting a resurgent interest for modern constructions thanks to its numerous advantages. Indeed, its widespread availability in the world, makes it affordable for most people especially those with low incomes. In addition it is entirely recyclable which makes it a renewable construction material. Above all, earthen materials' high hygroscopic and thermal properties are of great interest for the modern construction applications. This helps to reduce the energy consumption thanks to its ability to passively regulate the indoor temperature and air humidity for the occupants comfort.

However, earth materials still have to meet satisfactory mechanical strengths and water erosion resistance required by the current construction standards. The main drawback of this material is its low resistance to liquid water damages. Despite the design recommendations such as concrete or stonework footings, damp proofing and eaves extension [Walker, 2002] [Gernot Minke, 2009], the earthen loaded walls could remain vulnerable to heavy rain weathering and damages due to adverse events like flood or accidental damp. Therefore, most industrial applications and scientific studies recommend the use of cement or lime for earth stabilization [Molard et al., 1987] [Bell, 1996] [Bahar et al., 2004] [Browne, 2009]. But the high CO_2 footprint due to the high amount of the mineral binders added to these materials inhibits their sustainability [Van Damme, and Houben, 2017]. An overview of the vernacular construction techniques and the existence of ancient earth buildings [Beas, 1991] revealed the use of organic binders as earth stabilizers [Vissac et al., 2017].

The organic binders are natural polymers extracted from plants or animals and mixed with earth and water, generally for improving its water resistance.

A lookup to the sparse literature addressing the unfired earth stabilization with natural organic polymers, highlighted the difficulties to assess their efficiency. The variety of the natural organic polymers available, the state of which there are used, the combination with other chemicals and the composition of the stabilized soil are expected to influence the stabilization efficiency. This study aims to identify the stabilizing potential of some of those organic polymers thanks to a simple test procedure. Four organic polymers have been chosen for the study: polysaccharides (wheat starch and alginic acid) and proteins (casein and egg white albumin). Specimens were prepared with two types of soils and various amounts of each organic binder. Specimens were then tested according to their mechanical strength and their resistance to water.

2 MATERIALS AND PROCEDURE

2.1 Raw earths

Two types of soils were used for this study. The first one called "soil F" is a quarry fines from washing aggregate sludge provided with by a French concrete aggregates' supplier. It mainly consists of calcite, kaolinite, illite, quartz, dolomite and iron oxide minerals [Laborel-Preneron et al., 2017]. The second "soil N" is one of the most available soils in southern France. The soil N contains montmorillonite, chlorite, illite, albite, quartz and calcite minerals. The Table 1 shows the geotechnical characteristics of these soils.

Table 1: The geotechnical characteristics of the soils

	% Clay ($\leq 2\mu m$)	% Silt ($0,002mm - 0,063mm$)	% Sand ($0,063mm - 2mm$)	W_L	I_P	Normal Proctor Optimal water content w_{NPO} (%)	Normal Proctor Optimal dry bulk density ρ_{NPO} (kg/m^3)
Soil F	28.0	67.0	5.0	30	30	14.0	1988
Soil N	22.5	38,5	37	46	15	14.1	1880

The two base soils are noticeably different regarding their mineralogical composition and consequently, their geotechnical properties. Those particular properties are expected to variously influence the stabilization efficiency.

2.2 The organic binders

The Table 2 shows a quick description of the organic products used in this study. The column "Reference" gives the authors who have worked on the unfired earth stabilization with those types of molecules.

Two binders (casein and ovalbumin) are provided by a certified laboratory chemicals supplier. The Blancol and the casein are provided by a natural construction materials' company with technical form containing the details of the products. The authors then assume that the products contain essentially the required binder. All the binders used in this study were powders.

Blancol is an industrial paper paint glue made of natural wheat starch. Starches are main food reserve in plants and also used as carbohydrate nutrient source by man and animals [Srinivasan, 2013]. The linear 1-4 glucose (amylose) and the ramified one (amylopectin) are the basic polymers that compose starches [Huchette, 1968]. Their relative proportion in the starch differs according to the starch natural source. The wheat starch contains 29.2% of amylose and 70.8% of amylopectin [Tester and Morrison, 1990].

Alginic acid also call sodium alginate is the principal polysaccharide of the brown algae (Laminaria sp., Macrocystis sp., Lessonia sp. etc.) [Andersen et al., 2011]. It consists of two basic linear polymers that are the mannuronic acid and the guluronic acid (40% to 70%) [Andersen et al., 2011]. The alginate polymers are therefore a sequential combination of these latter. Many industrial applications of the alginate use its gelling properties [Srinivasan, 2013]. When a calcium source is added to a solution containing alginic acid, an "egg box" like structure gel is formed where the calcium ions crosslink the guluronic-manuronic polymers [Srinivasan, 2013].

Casein is a milk protein. It constitutes over 70% to 80% of the total bovine milk protein. It belongs to the family of the phosphoproteins which biological role is the phosphate transport for the bones growth [Swaisgood, 2003]. The casein polymers are built of twenty eight amino acids [Brigando, 1941]. [Horne, 2014] reported that the word "casein" covers many molecules and the main ones are the α_{s1}, α_{s2} , β, and κ-caseins. The industrial extraction of the casein from the milk, consist of using an acid or a biological enzyme for its precipitation [Beau, 1941]. In an alkali solution, the casein is dispersed. But in the case study, the hydrated lime was used rather than the ammonia because of its uncomfortable odour. During the world war I, natural glues made of casein were used for the aircraft industry [Anger and Fontaine, 2013].

Ovalbumin is a chicken egg white albumin. The albumin is also a phosphoprotein available in the animals' blood. It is main protein of the egg white (54% to 60%) Gauthier. 2000 cited by [Anger, and Fontaine, 2013]. The albumin amphiphilic properties entail its surfactant abilities which are widely used in the food industry. Over a temperature of 60°C, the globular structure of the albumin is irreversibly modified: The polymer chains interlock and jam the water molecules in a rigid network [Anger, and Fontaine, 2013]. This explains the structure of the cooked egg white.

2.3 The specimens preparation

Several specimens were prepared with the two base soils only as control samples on one hand, and their mixtures with respective four organic binders pre-activated or not with 0.1% of a hydrated lime on the other hand. The binder amount was 1% and 4% of the soil dry weight. Small scale test samples were first done in order to quickly assess the mixtures water resistance. Then mechanical tests were performed on thorough

Table 2 : The organic polymers used in this work

Molecules group	Binder	The supplier's technical specifications	Reference
Polysaccharides	Blancol	-	[Alhaik et al., 2017]
	Alginic acid	Water content ≤15% $6{,}5 \leq pH \leq 8{,}5$	; [Galán-Marín et al., 2010] ; [Dove et al., 2016] ; [Pinel, 2017] ; [Pinel et al., 2017] ;
Proteins	Casein	Water content 10% $pH = 4{,}7$ Granulometry: $98\% \leq 400\mu m$	[Mileto et al., 2012]
	Ovalbumin	Solubility in water 50mg/ml	[Vissac et al., 2017]

shape specimens (compressed cylindrical specimens) made of the conclusive mixtures.

- *The specimens for water resistance test*

Small parallelepipedic samples were hand molded in a $47mm \times 35mm \times 15mm$ plastic framework with various mixtures of the soils and the binders (Figure 38 (a)). The soil and the binder were dry homogenized. Then, the water was progressively added until the desired consistence was reached. The real water content of this mixture was measured. The specimens were stored in a chamber controlled at 20°C and 50% of relative humidity until a constant weight.

- *The specimens for the compressive strength*

The cylindrical specimens were prepared with mixtures of the soil and the binders using the same water content as the Normal Proctor Optimum water content of the control mixture Figure 38 (a). The soil was first mixed with water at 10% of water content and stored 24h hours in a hermetic plastic bag in order to make sure that it absorbs enough water before the binder addition. Then, the required quantity of binder was manually homogenized with the pre-humidified soil. The remaining water was finally added and mechanically mixed. The necessary amount of this material was placed in a cylindrical mold [AFNOR NF EN 13286-53, 2005] and pressed at both sides to get a 50 mm diameter and 50 mm height cylindrical specimen. The molding pressure were kept for 10s at 10MPa. The weight of the humid mixture was calculated according to the equation (1) in order to get a specimen with an equivalent dry bulk density of the reference mixture.

$$\boldsymbol{m_h = \rho_{d_{NPO}} . (1 + w_{NPO}) . \pi . h . \frac{\emptyset^2}{4}} \qquad \textbf{(1)}$$

The cylindrical specimens were dried at the same conditions as the parallelepipedic ones before being tested.

2.4 The tests procedures

- *The water resistance test*

The parallepipedic specimens were immersed in a box filled with water. The time to the total dislocation was measured as the water resistance of the material. [Gernot Minke, 2009] considered similar tests like DIN 18952 Part 2 which implied a prolonged contact of the earth with liquid water as sever and not realistic. With the current global warming effects, heavy rains and floods are more likely to occur even in some areas of the globe that are basically assumed to be arid. It is therefore important to insure that in case of these accidental events, the loaded earthen walls in contact with liquid water wouldn't collapse instantly in order to permit the occupants evacuation. This precaution resembles to the ultimate limit state criterion.

Figure 38: The dry cylindrical and parallelepipedic specimens (a); Water resistance test procedure (b)

- *The Unconfined compressive test*

The unconfined compressive test was performed on the cylindrical specimens. The test was performed under force driven control at the speed of 0,2 kN/s. A wet mechanical strength was also measured for some mixtures that passed the aforementioned water resistance test according to the standard NF XP 13-901 [AFNOR, 2001]. The specimens were immersed for two hours in a box filled with water (Figure 38 (b)), then withdrawn and cleaned with a slightly wetted sponge and placed in a hermetic plastic bag for forty-eight hours before the unconfined compressive test.

3 RESULTS AND DISCUSSIONS

3.1 The water resistance

The Table 3 summarizes the results of the water resistance test on the parallelepipedic specimens. The measured water content of the mixtures are also available in this table.

Table 3 : The water resistance test on the parallepipedic specimens

Stabilisation			The test results for each soil.							
Binder	Binder proportion (% wt)	Pre-activation method	Soil F				Soil N			
		Lime $Ca(OH)_2$ (% wt)	Mixture Code	Mixture water content w (%)	Cracks after drying	Water resistance	Mixture Code	Mixture water content w (%)	Cracks after drying	Water resistance
Ref.	0%		F	28.7	no	2 min	N	29.9	no	6 min
	0%	0.1%					N0.1L	29.7	no	7 min
Blancol	1%		F1B	30.5	no	24 min	N1B	29.1	no	3 days
	4%		F4B	36.7	no	3 days	N4B	38.7	yes	3 days
Alginic acid	1%	0.1%	F1A	34.1	no	240 min	N1A0.1L	35.5	no	140 min
	4%	0.1%					N4A0.1L	51.2	yes	7 min
Casein	4%						N4C	35	no	17 min
	4%	0.1%					N4C0.1L	52.1	no	7 days
Ovalbumin	4%						N4O	44.8	no	7 days

The non-stabilized soils (soil F and soil N) immersed in water, totally disintegrate within 10 minutes.

One can gather the water resistance of the respective mixtures into three categories as proposed in the Table 4. The time to disintegration minimum of 120 min refers to the [AFNOR, 2001] test protocol. Similarly, a softer limit of 45 min were required by the German standard DIN 18952 Part 2 cited by [Gernot Minke, 2009]. All the category 3 specimens of the case study also failed this latter requirement.

Table 4: Mixtures classification according to their water resistance

Water resistance category		Time to desaggregation	Cracks after drying	No cracks after drying
Best	1	$\geq 1\ day$	N4B	N4O; N4C0.1L; N1B; F4B
Medium	2	$120\ min\ - 1\ day$		F1A0.1L; N1A0.1L
lower	3	$\leq 120\ min$	N4A0.1L	N; F; N0.1L; F1B; N4C

The addition of 4% of casein and ovalbumin significantly improves the water resistance of the soil N. This can be explained by the fact that their amphiphilic peptic polymers establish a strong water barrier around the clayey particles by adsorption or electrostatic interaction [Vissac et al., 2017]. The hydrophobic pole of those chains fixes on the –OH sites of the clay particles while their hydrophilic poles prevent water molecules from accessing the clays. This mechanism varies according to the type of clay mineral and the medium pH. The electronegative surface of the montmorillonites can fix many layers of protein chains when the pH of the solution is close to the isoelectric point of the binder [Anger, and Fontaine, 2013]. It is worth mentioning that unlike the ovalbumin, the casein alone has no effect on the soil's water resistance. The albumin which is the main protein in the egg white is naturally soluble in the water. It is then easily driven by water to interact with the clayey particles; whilst the casein molecules immediately form micelles once in the water. In these spherical clusters like particles, the hydrophobic poles are turned towards the center leaving the hydrophilic poles in the water. No interaction is therefore possible with the clayey particles. The addition of a few amount of some chemicals (here the lime) increases the pH of the medium which disperses the casein micelles [Fox, and Brodkorb, 2008] and helps then the interaction with the clayey particles.

The soil N mixed with 1% of Blancol and the soil F mixed with 4% of Blancol also showed significant improvement in the water resistance. The Blancol could have acted as glue on the soils particles while drying, which is its basic industrial property. However, only 1% of the wheat starch entails this improvement on the soil N while 4% were necessary on the soil F. Two reasons may explain this difference. First, the particle size distribution of the two soils is strongly different. The soil F which is far finer than the soil N could require more binder to cover enough the clayey particles in order to limit their exposure to the water. The second reason could be linked to the mineral and chemical differences between the soils. The kaolinite and the calcite in the soil F may interact fewer with the wheat starch than the illite, the chlorite and the montmorillonite contained in the soil N.

The addition of the alginic acid at a limit amount of 1% combined with 0.1% of lime respectively on the soils N and F slightly improves their water resistance. Unlike [Dove et al., 2016], [Pinel, 2017] also highlighted the soil water resistance improvement potential by a similar test. However, samples tested in this study totally disaggregated within 2h to 4h while the ones of this latter could last 3 days in water with damages only due to the cracks. The alginic acid gelling method could explain this difference. [Pinel, 2017] used not only lime as calcium source for the alginate gel formation, but also sodium Hexametaphate and Glucono-δ-lacton (GDL) as its kinetic controller in order to get a homogeneous gel matrix in the soil. This improves the efficiency of the alginate on the material water resistance.

During the drying process, heavy cracks appeared on the specimens of the soil N with 4% of Blancol, and moderate cracks were observed on the ones of the soil N with 4% of alginic acid activated with 0.1% of lime. No cracks were found on the specimens of soil N with 1% of Blancol and 1% of alginic acid activated with 0.1% of lime. This reveals a pessimum effect due to the binder amount added to the soil. Indeed, the authors remarked that the Blancol and the alginic acid are water expansive. Over a certain amount in the soil, their related shrinkage causes cracks in the material. For the soil N, the threshold lies between 1% and 4%. Yet, no cracks were reported on the soil F specimens with 4% and 1% with Blancol. This highlights the significant role of soil properties. In fact, the swelling minerals like montmorillonite contained in the soil N could underlie additional shrinkage related cracks that explain this different behavior of the two soils. All those observations were reported on materials prepared at the consistence of conventional adobes. [Alhaik et al., 2017] also reported shrinkage cracks on mixtures with quarry fines (soil F) and 1% of pregelatinized starches at a controlled pouring consistence. At the same consistence, the control mixture did not crack. The cracks were then caused by these type of starches. Without the real source of those starches and comparing these results to the case study, we can conclude that for a given soil, the material's consistence should be optimized accordingly to the type of the binder.

3.2 The unconfined compressive strength

The wet and dry unconfined compressive strength of the control mixtures and the best water resistant ones were reported in the Figure 39. The mixture codes stand for the same definitions as presented in the Table 3.

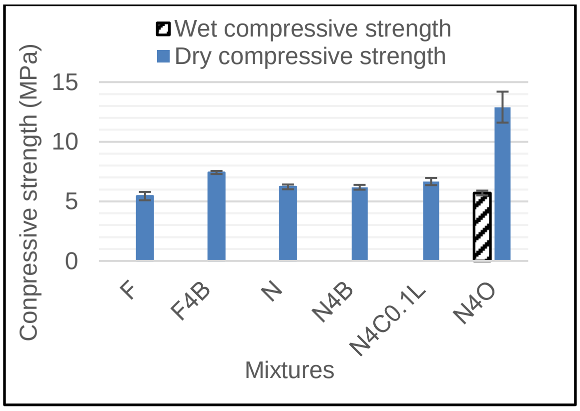

Figure 39 : The unconfined compressive strengths

The addition of 4% of the ovalbumin in the soil N increases its dry unconfined compressive strength to two times. The Blancol and the casein activated with 0.1% of lime showed no improvement on the dry unconfined compressive strength of the soil N. 4% of Blancol slightly increases the dry unconfined compressive strength of the soil F. No crack were found on any of the so manufacured cylindrical specimens. The mixture with 4% of ovalbumin with the soil N gave wet unconfined compressive strength over 5 MPa. This value is far higher than the minimum of the 1 MPa requirement of the French cement stabilized concrete earth blocks (CEB). All the other samples failed the two hours immersion in the water.

This difference of behavior at the wet state between the specimens of the two manufacturing processes could be due a problem of homogeneousity. Unlike the ovalbumin which is naturally soluble in the water, the Blancol and the casein require more water to interact with the clay particles. Since the mixing water content of the cylindrical specimens were the same as the control mixture (14%), one can assum that their were no or a few water available to drive the binder in the clay matrix.

4 CONCLUSION

Two polysaccharides (wheat starch and the alginic acid) and two proteins (casein, and the ovalbumin or chicken egg white albumin) were used two types of soil. The small scale water resistance test highlighted the promising potential of the ovalbumin, the casein and the Blancol. However, the unconfined wet compressive test performed on compressed earth cylinders only confirmed the binding performance of the ovalbumin at 4% of incorporation. This implies that the manufacturing procedure can influence the efficiency of a given binder on the soil. In addition, it was found that for some organic binders such as the casein and the alginic acid, a chemical preactivation is necessary. For alginic acid, the availability of calcium source in the mixture is not sufficient. The gel forming kinetic controller should also be used.

The cracks observed on the soil N with 4% the wheat starch and the alginic acid showed the importance to optimise the amount of the binder according to the type of soil.

Overall, the outstanding results obtained with 4% of the ovalbumin reassured the authors that some organic polymers addition to the earth can rise it to the range of convenient modern construction material.

Additional tests should address the binding effect of the ovalbumin and the casein on the soil F. The mixtures could be prepared at the same consistence in order to investigate the role of the water content on the organic binder efficiency. Other family of organic natural polymers can also be tested.

At last, an assessment of the cost and the environmental impact of the best mixtures can help lower the binder addition to the strictly necessary amount, which is called "the spicy like" quantity by [Van Damme, and Houben, 2017].

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