CAST, COMPACTION, VIBRO-COMPACTION OR EXTRUSION: PROCESSING METHODS FOR OPTIMIZING THE MECHANICAL STRENGTH OF RAW EARTH-BASED MATERIALS

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Abstract

In the last few years, raw earth construction has recovered much consideration due to its low environmental impact, its local character and its recyclability. However the strength of this material is really fluctuating as a consequence of soil's variability and the different methods that are used in vernacular earth construction. The aim of this study is to identify the mechanisms that increase the strength of this material. The optimization of the processing method of raw earth's blocks is sought in order to get better strengths systematically for different sorts of soils. All of these soils are extracted from the same region, Brittany, in order to insist on the local character of this material.

For three sorts of soils from Brittany this study will focus on four different processing methods: casting, compaction, vibro-compaction and extrusion. These soils will be mixed with water only or water and Sodium-hexametaphosphate which acts as a dispersant. The rheological behaviour of each soil will be adapted to the different processing methods. The fact that, for earth-based materials, the compressive strength at the dry state depends on its dry density will be shown. Thus it will be displayed that the processing method, and the use of dispersant that allows to reduce the water content during the processing, can be efficient to enhance the dry density and consequently the compressive strength of all of the selected soils. Those strategies are also efficient to improve the process robustness for ensuring high levels of compressive strength and dry density for raw earth construction.

This study highlights that some of these methods could be used soon at a semi-industrial scale, to produce a structural material that needs to achieve compliance with modern standards without hydraulic binders.

Keywords:

Earth-based materials, processing, rheology

1 INTRODUCTION

In the context of "nearly out of control" global warming it is really important to improve our way to build making 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, vernacular raw earth construction methods are leading to uncertain mechanical characteristics with no guaranteed minimal values. It is also difficult to achieve a mix design that permits a fast hardening and that can ensure reproducible mechanical characteristics. Indeed, due to the high variability of soils that are used in earthen construction, induces a large range of earth based materials mechanical strength. Furthermore some previous studies have shown that for a defined earth based material, strength and mechanical characteristics depends on dry density. [Bruno et al. 2015 ; Moevus et al. 2015 ; Bruno 2016 ; Bruno et al. 2017 ; Gallipoli et al. 2017 ; Menasria et al. 2017a ; Perrot et al. 2018].

For these reasons, since the construction industry dictates that a structural material needs to achieve needs to comply with modern standards, there is a clear need to systematically improve the strength of earth based materials at the highest level. The recent trend in this research field has been to apply scientific knowledge and expertise, developed by the concrete industry, to earthen construction [Landrou et al. 2014; Moevus et al. 2015; Ouellet-Plamondon and Habert 2016].

According to this observation there are several options to optimize and control (to ensure performance reproducibility) the strength of raw earth material. One of the options is to optimize the granular skeleton of the material in order to increase its dry density and thereby its strength [Moevus et al. 2015; Menasria et al. 2017a; Perrot et al. 2018]. Another option is to add hydraulic binder to shorten the hardening of the material and to ensure a minimum strength and decrease water sensibility [Walker and Stace 1997; Venkatarama Reddy and Prasanna Kumar 2011a; Venkatarama Reddy and Prasanna Kumar 2011b; Khelifi et al. 2013; Tripura and Singh 2014; Landrou et al. 2014; Khelifi et al. 2015; Miccoli et al. 2015]. In this paper the use of hydraulic binder is avoided in order to limit environmental impact.

A third option that stems from concrete mix design, is to improve the workability of the material by deflocculating the clay-based 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.

It has also been shown that better controlling the processing method, particularly for the compacted and hypercompacted earth [Bruno et al. 2015, Bruno 2016 and Bruno et al. 2017], is a good solution to systematically optimize mechanical strength.

In this work, the first option is used to design a material from Breton kaolin clay and fine and coarse sand with a continuous particle size distribution. Two other soils extracted in Brittany are also used. A first aim of this study is to optimize the rheological behaviour of the different local soils for four different processing methods: Casting, compaction, vibro-compaction and extrusion. The third option is used here to improve the rheological behaviour of each soil to each processing method. Another goal of this study is to show the influence of the compaction effort on the mechanical strength of different materials. Finally it also tries to identify the most effective processing methods for the three different soils in order to obtain systematically the highest mechanical properties for raw earth based materials.

2 MATERIALS AND METHODS

2.1 Three different kind 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 sands.

The kaolin clay has been provided by Imerys and has been quarried at “Kaolins de Bretagne”, Ploemeur. This clay has a specific gravity of 2.65 and a specific surface area of 10 m^2/g (given by the provider).The particle size distribution of this clay has been measured using a laser particle size analyzer [Menasria et al. 2017a; Perrot et al. 2018]. The largest clay grain size is approximately 10 μm and the mean clay grain size about 4 μm.

The fine sand, has a grain size distribution ranging between 63 μm and 200 μm and the coarse sand has grain size ranging from 0 to 4 mm. The fine sand particle size distribution (PSD) has been obtained by laser diffraction and the coarse sand PSD was obtained by sieving. The grain size distributions of the three materials are plotted in Fig. 1.

Dreux and Gorisse proposed a method [Dreux and Festa 1998] to determine an optimized ratio from sand to gravel in order to obtain the densest aggregates packing. To optimize the PSD of this kaolin-based mix this method has been used in previous works [Menasria et al. 2017a; Perrot et al. 2018]. It has led to the optimized PSD of a ternary mix of clay/fine sand/coarse sand. This composition leads to the highest mechanical strengths that can be reached with this ternary mix. The mix is composed by mass of 17% of kaolin clay, 23% of fine sand and 60% of coarse sand. The optimized PSD of this ternary mix is plotted in Fig. 2.

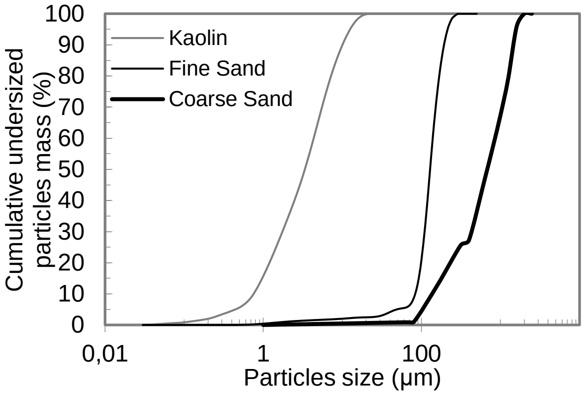

Fig. 15: Particle size distribution of kaolin clay and sands.

Local soil extracted in Redon, Brittany (rammed earth)

The second material that has been tested is a rammed earth from Redon (Brittany, France). 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 is plotted on Fig. 2 and has been obtained by laser diffraction and sieving.

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

The third 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. 2017a; 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), determined by XRD analysis before and after thermolysis at 550°C on some of the samples that has been tested. These swelling clays couldn’t be found on all of the samples but this soil has been mixed up 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. 2 and has been obtained by laser diffraction and sieving.

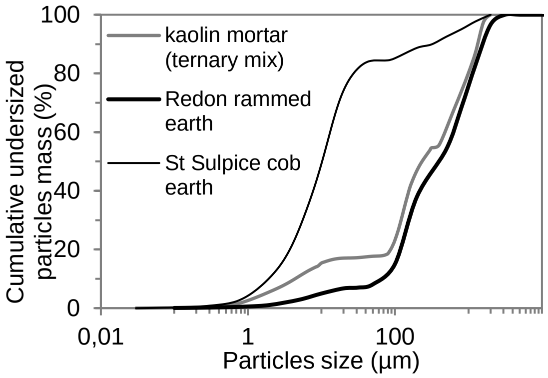

Fig. 16: Particle size distribution of kaolin mortar and Redon and Saint-Sulpice soils.

2.2 Use of a dispersant

Hexametaphosphate (HMP) is used as a dispersant in this study to make the mortar more easily flowable 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. For the soil from Saint- Sulpice-La-Forêt, the mass ratio of HMP is 0.3% of the dry material. The choice of this dosage was made using the same methodology than the one used for the kaolin mortar in [Perrot et al. 2016]. For the soil from Redon the same mass ratio of HMP as the kaolin mortar has been chosen.

2.3 Four different processing methods

For all of these methods the earth mix has been made using a high capacity Hobart mixer following the same procedure that is used by [A. Perrot et al. 2018].

Each of the samples has dried first in a stabilized atmosphere (20°C, 50%HR) and then in a heat chamber at 50°C until the sample weight has been stabilized. At this stage the sample was considered dry. Then the compressive strength of each sample has been measured using a 50kN loading frame. The test has been carried out at a constant velocity of 0.5 mm/min which is in agreement with the French national standard recommendation for soil testing NF EN ISO 17892-7 (test duration ranging between 2 and 15 min, maximum strain rate of 2% per minute).

All of the compressive tests have been carried out with sample of an aspect ratio of one, and it is considered that mechanical measurements can be compared even if their geometries are different (cylindrical or prismatic shapes). It is acceptable since it has been shown that, at a same aspect ratio, the strength variation due to shape variation is lower than 5% (S.T. Yi et al. 2006). The chosen aspect ratio is in agreement with the French national standard recommendation for mechanical strength measurements on mortars NF EN 196-1 (AFNOR).

For the different soils tested in this paper, several samples has been tested out with different processing methods: casting, compaction, vibro-compaction and extrusion. These processing methods are described in the following subsections.

Casting

For each kind of soil, the mix is prepared at a quite high water content (slightly higher than the plastic limit of the material without HMP). Then the mix is cast in cement mortar 40*40*160 mm^3 moulds.

Compaction

Cylindrical samples with a diameter and a height of 70 mm are compacted in a special mould (shown on Fig.3) with a 200kN loading frame at different maximum vertical forces ranging from 20kN to 60 kN. In this mould, the material is compacted by two rams in order to have a double effect compaction and to allow a better distribution of the stress in the material. Between the two rams and the material surfaces, two perforated aluminium discs are implemented with filter paper on top in order to ease the drainage of interstitial water and retain the finest soil particles that could be carried by interstitial water.

The compaction rate is ranging between 2 and 5 mm/min (2 mm/min for most of the samples). For each kind of mix, 3 different maximum vertical stresses have been applied to create different samples: 5.2 MPa, 10.4 MPa and 15.6 MPa. The aim is here to show that the maximum vertical stress that is applied to the sample is influencing its mechanical properties. In this case, the water content of the soil is very low.

Vibro-compaction

This procedure is almost the same as the compaction: the mould, the compaction rate and the different maximum vertical stresses applied on the samples are the same. But three compressed air vibrators are set up on the mould and are vibrating during all the compaction process (Fig.3). The compressed air has an inlet pressure of 7 bars and the valves are wide open. In this case, the water content of each soil is the lowest.

Fig. 17: Compaction mould and vibrators set up on the mould under the loading frame.

Extrusion

A 70 mm cylindrical screw extruder is used to push the raw earth based mix throught a 35 mm diameter extrusion die. When the extruded material is leaving the extrusion die, it is sliced in 35 mm high samples, in order to have samples with an aspect ratio of 1. The water content of the soil is commonly a little bit lower than the water content of a cast soil (under the plastic limit of the soil).

3 RHEOLOGICAL BEHAVIOUR OF THE MATERIAL AND FORMING PROCESS: OPTIMIZATION.

The tests presented in this part of the study are focused on the kaolin mortar behaviour, but the same kind of trend has been noticed for the two other soils. At the end of this part a table (Tab. 1) indicates the different optimal water contents for the different soils (with dispersant or not) and the different forming processes.

3.1 Different optimal water contents for different forming processes

On Fig.4, that stems from [Perrot et al. 2018] study , the evolution of the dry density of samples that have been casted or compacted (static or dynamic compaction) with the initial water content of the soil mortar is plotted. It is easily noticeable that the optimal water content to obtain the highest dry density of the material differs with the forming process.

Indeed for the kaolin mortar, and for a dynamic compaction forming process the optimal water content required is only 5.5% while for the casting process the optimal water content is about 14%. To obtain the material with the best mechanical strength, it is mandatory to aim for the highest dry density achievable regardless of the forming process [Bruno et al. 2015; Moevus et al. 2015; Bruno 2016; Bruno et al. 2017; Gallipoli et al. 2017; Menasria et al. 2017a; Perrot et al. 2018]. For static compaction, the optimal water content is an intermediate content of 10% to obtain the maximum dry density. For 3 different forming processes, the rheology of the wet material is fluctuating in order to obtain the highest mechanical characteristics of the material.

These results highlight that the rheology of the wet material has to be optimized regarding the forming process that is used to shape the earth sample.

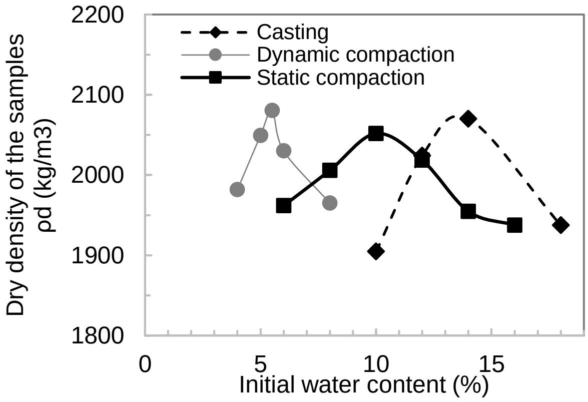

Fig. 18: influence of the initial water content on the dry density of the samples for different forming processes.

One interesting fact is also that for the static compaction, the final dry density of the material depends on the level of loading applied during the forming process. In Fig. 4, all the values related to the static compaction result from measurement on samples that have been achieved by static compaction performed at a maximum load of 25 MPa. An increase of the vertical stress from 25 to 45 MPa applied on the wet material at an optimal water content of 10% results in an increase of the dry density of the sample from 2060 kg/m^3 to 2100 kg/m^3 [Perrot et al. 2018, Menasria et al. 2017]. Using higher energy of compaction could lead to higher mechanical properties for a same material as it is noticed in [Bruno et al. 2015] study.

In this paper, one of the aim is to assess the improvement brought by vibration for the 3 different kinds of soil while adding vibration to compaction in the vibro-compaction process.

3.2 Optimizing the dry density by using a dispersant

As stated above, the HMP is used as a dispersant in order to improve the workability of the material by deflocculating the micro-sized clay particles structure, and thus reducing the interaction force between the clay particles in the different soils. This allows to reduce the initial water content of a wet soil to obtain the same rheology. By reducing the initial water content of the wet material, the final porosity of the dry material is lower.

It also permits a better dispersion of the clay particles as [Perrot et al. 2016] study has shown, that improves the mechanical strength of the dry material.

The evolution of the compressive strength of 2 mixes of kaolin mortar (with and without HMP) with the dry density of the material is plotted in Fig. 5 [Perrot et al. 2018, Menasria et al. 2017a]. In these results, 2 distinct curves can be highlighted, the first one for the mix containing HMP and the second one for the mix without HMP. For both of these curves the mechanical strength increases exponentially with the dry density of the material. However, considering that the HMP permits a better dispersion of the clay particles, it is obvious on Fig.5 that for a same density, the mixes with HMP show higher mechanical strengths.

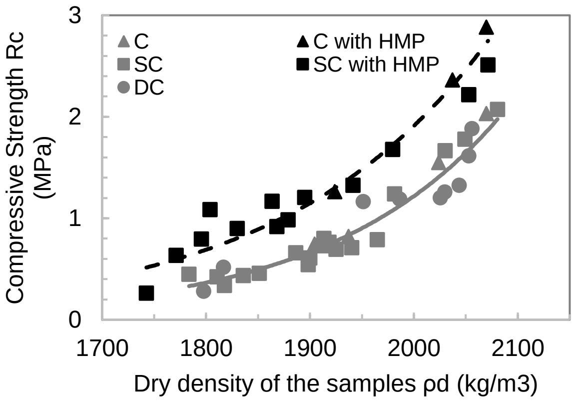

Fig. 19: Evolution of the compressive strength of the sample after drying with the dry density for different forming processes and with and without HMP addition

As in the works of [Perrot et al. 2018, Menasria et al. 2017a] it is important to mention that the forming process is not influencing the final mechanical strength of the material. For two samples with the same dry density, but achieved with two different forming processes, their mechanical strengths will be similar.

3.3 Different water contents, for different forming processes, mix and sorts of soil

Regarding these remarks, the rheology of each mix of soil has been adapted to the different forming processes. Tab. 1 is showing the different water contents that have been selected in this study.

Soil	Mix	Initial Water Content (%)			
		Casting	Compaction	Vibro-compaction	Extrusion
Kaolin mortar	Kaolin	**14%**	**10%**	**9%**	**10-11%**
	Kaolin-HMP	**12%**	**8%**	**7.5%**	**9-10%**
Redon	Redon	**22%**	**14.5%**	**14%**	**17.5%**
	Redon-HMP	**19-20%**	**13.5%**	**13%**	**17%**
Saint-Sulpice	St-Sulp	**30%**	**20%**	**19.5%**	**23%**
	St-Sulp-HMP	**28%**	**18%**	**17.5%**	**21%**

Tab. 11: Initial water content of the soils regarding the mix and the forming process

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4 INFLUENCE OF THE COMPACTION EFFORT ON THE STRENGTH OF THE MATERIAL FOR COMPACTION AND VIBRO-COMPACTION

As explained previously, one of the aim of this study is to highlight that, for a compaction (C) or a vibro-compaction (VBC) process, the maximum vertical stress that is applied to the sample is influencing its dry density and its mechanical strength.

Several previous studies, [Bruno et al. 2015, Bruno 2016 and Bruno et al. 2017] are reporting that an increase of the compressive energy in compaction process from 25 MPa to 100 MPa leads to an increase of the dry density of the sample. However, the increase in dry density is not linear when the compressive stress is increasing. Several studies have also highlighted that the mechanical strength of raw earth material increased with its dry density [Bruno et al. 2015; Bruno 2016; Bruno et al. 2017; Gallipoli et al. 2017; Moevus et al. 2015, Perrot et al. 2018, Menasria et al. 2017a].

For each sort of soil and each mix, for compaction and vibro-compaction processes, one or two samples have been carried out at three different applied stress levels: 5.2 MPa, 10.4 MPa and 15.6 MPa. For the kaolin mortar, the compressive strengths and the dry densities fluctuating with the compaction stress for two mixes (with and without HMP) and two processes (Compaction and Vibro-compaction) are plotted on Fig.6 and Fig.7.

First of all, the results plotted in Fig. 6 confirm the fact that for each of the mix, and for both compaction and vibro-compaction, the increase of the compaction stress is leading to an increase of the dry density:

- For the compaction of Kaolin the dry density is fluctuating from the mean value of 2003 kg/m^3 to the mean value of 2073 kg/m^3 while the compaction stress is ranging from 5.2 MPa to 15.6 MPa.
- For the vibro-compaction of Kaolin with HMP the dry density is fluctuating from the 2052 kg/m^3 to 2107 kg/m^3 while the compaction stress is ranging from 5.2 MPa to 15.6 MPa.

Then, the same trend is noticed for the compressive strength, which is increasing with the compaction stress according to Fig.7:

- For the compaction of Kaolin the compressive strength is fluctuating from the mean value of 1.3 MPa to the mean value of 1.6 MPa while the compaction stress is ranging from 5.2 MPa to 15.6 MPa.
- For the vibro-compaction of Kaolin with HMP the compressive strength is fluctuating from 2.3 MPa to 2.5 MPa while the compaction stress is ranging from 5.2 MPa to 15.6 MPa.

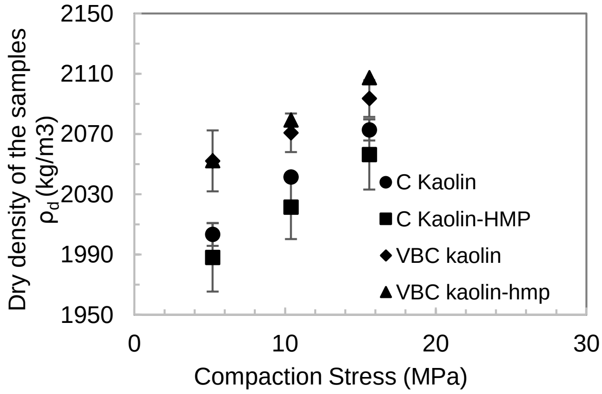

Fig. 20: Evolution of the dry density of kaolin mortar samples with the compaction stress.

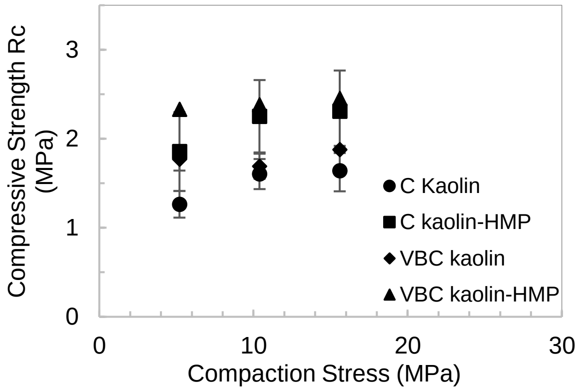

Fig. 21: Evolution of the compressive strengths of kaolin mortar samples with the compaction stress.

Soil	Mix	Vertical stress applied on the sample (MPa)	Mean compressive strength of the samples (MPa)		Mean dry density of the samples (kg/m^3)	
			Compaction	Vibro-compaction	Compaction	Vibro-compaction
Kaolin mortar	Kaolin	5.2	1.3	1.8	2003	2052
		10.4	1.6	1.7	2042	2071
		15.6	1.6	1.9	2073	2094
	Kaolin-HMP	5.2	1.9	2.3	1988	2052
		10.4	2.3	2.4	2022	2079
		15.6	2.3	2.5	2056	2107
Redon	Redon	5.2	2.1	2.2	1874	1885
		10.4	2.5	2.5	1902	1919
		15.6	2.5	3.0	1923	1949
	Redon-HMP	5.2	2.4	2.3	1889	1880
		10.4	2.6	2.8	1913	1927
		15.6	3.0	3.1	1931	1953
Saint-Sulpice	St-Sulp	5.2	5.0	5.0	1706	1728
		10.4	5.3	6.1	1727	1743
		15.6	5.6	7.1	1739	1785
	St-Sulp-HMP	5.2	5.3	6.1	1733	1743
		10.4	5.3	6.4	1751	1767
		15.6	6.2	6.7	1767	1788

Tab. 12: Mechanical characteristics of different sorts of soil with and without HMP, for compaction and vibro-compaction at different levels of compaction effort.

For both of the parameters, an overall trend seems to appear: vibro-compaction is leading to better mechanical strength than compaction, for a given soil. The addition of dispersant for a given process method is also increasing this characteristics.

This trend is also noticeable for the other sorts of soil that have been studied following the same method. The resulting mean values of this experimental campaign are plotted in Tab.2.

Increasing the compaction load leads to increase the mechanical characteristics of all sorts of soil samples carried out with both compaction and vibro-compaction processes. The addition of dispersant, for each sort of soil and forming process, is leading to better mechanical properties. Finally vibro-compaction, for all of the soils, is leading to better mechanical properties than compaction: the vibro-compaction process could almost be considered as a “mechanical dispersant”

5 INFLUENCE OF THE PROCESSING METHOD ON MECHANICAL STRENGTHS FOR DIFFERENT SOILS.

As vibro-compaction seems to be a good way to improve the mechanical characteristics of raw earth based materials compared to compaction, it still has to be compared with other processing methods for different sorts of soil with and without HMP. It will permit to have an overview of the potentials of these methods and their compliance with three significantly different sorts of soil:

- Kaolin soil, which is the densest but leads to low mechanical properties, due to the small specific surface area of kaolinite that can be considered as a low strength potential clay.
- Redon rammed earth, a lighter earth, with a low clay content and high silt content but that leads to intermediate strength potential due to the composition of its clay content: kaolinite, illite and chlorite. Illite and chlorite have higher specific surface areas and the interactions between these clay particles are stronger.
- St-Sulpice-La-Forêt cob earth, the lightest and the finest earth, with a higher clay content. This earth leads to the highest strength potentials because of its clay content: kaolinite, illite and smectite (swelling clay). The interactions between these clay particles are the strongest.

These three different potentials of strength for these soils are already highlighted in Tab.2. The following investigation will confirm this observation.

In this part the four processes, casting, compaction, vibro-compaction and extrusion have been tested on all of the soils with and without HMP. The Mechanical strengths evolution compared to the dry density of the three different materials with and without HMP are plotted in Fig. 8 and Fig.9.

First of all the results plotted on Fig. 8 and Fig. 9 confirm that each of the selected soils leads to different mechanical properties that covers a very broad range of the sorts of soil that could be used as construction materials in Brittany. These results are also confirming that the forming processes are not influencing the final mechanical strength of the different materials.

Then in Fig. 8, for the samples carried out without HMP addition, it seems that for all of the different soils, the vibro-compaction is the best processing route to reach high levels of dry density and compressive strength regularly.

For the kaolin mortar, extrusion seems to be an efficient forming process too, as compaction even if compaction is leading to lower mechanical properties. The casting process is leading to a wide range of different mechanical properties and seems to be an inappropriate processing method to use for reaching guaranteed mechanical characteristics. It is probably due to the difficulty to ensure the same process for each sample, as the process is managed by hand.

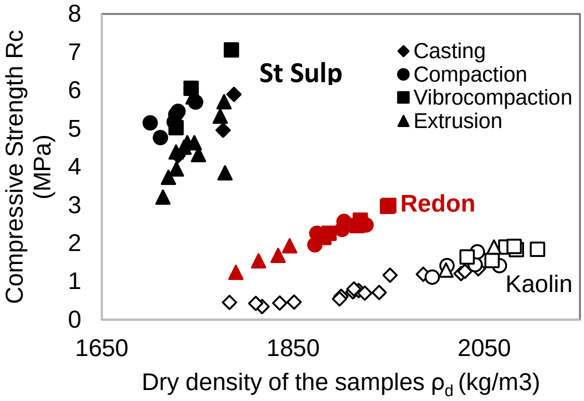

Fig. 22: Evolution of the compressive strength and the dry density of earth samples made with different sorts of soil for four different forming processes.

For the Soil from Redon, both compaction and vibro-compaction are leading to good and high levels of compressive strength and dry density, while extrusion is carrying out to lower mechanical characteristics. It can be explain by the fact that the clay content of this soil is really low, and that the silty and sandy granular particles are probably interacting with the inner surface of the extruder which causes friction on the surface of the sample that finally reduces density and its mechanical strength.

And for the soil extracted in Saint-Sulpice-La-Forêt vibro-compaction seems to be the best process method to ensure systematically a high compressive strength. The other methods are leading to good mechanical properties, but these properties are too variable.

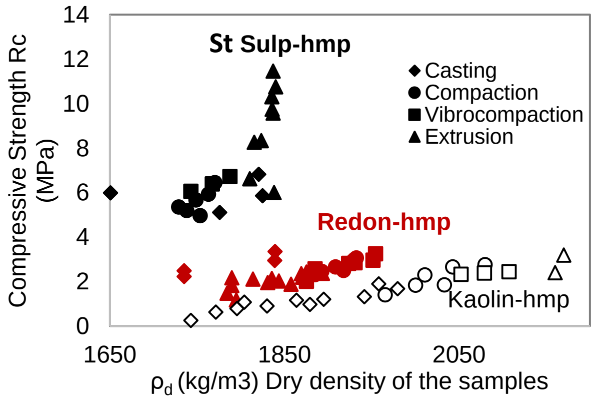

Fig. 23: Evolution of the compressive strength and the dry density of earth samples made with different sorts of soil, for four different forming processes, with HMP.

In Fig. 9, the samples have been carried out with HMP addition. It seems that for all of the different soils, the vibro-compaction is a very good way to aim for high levels of dry density and compressive strength regularly. However, for the soil extracted in Saint-Sulpice-La-Forêt and the kaolin mortar, the extrusion process is leading to the best mechanical properties with the addition of a dispersant. For the soil extracted in Saint-Sulpice-La-Forêt, its higher clay content can explain its good behaviour as an extruded material. However, the addition of a dispersant seems to be really important in order to obtain high mechanical properties when the material is extruded. For the soil extracted in Redon, even the addition of a dispersant is not enough to make it easily extrudable. For all of the soils studied here, a processing method allows to aim for a compressive strength higher than 2 even 2.5 MPa.

Finally, two process methods appear to be optimized methods to aim for high levels of mechanical properties:

In the case of vibro-compaction, for all of the soils studied here, with and without HMP, it seems to be a good forming process to achieve high compressive strength earth block regularly. This forming process is leading in the best cases to maximum compressive strengths of: 2.5 MPa for kaolin-HMP, 3.1 MPa for Redon-HMP and 7.1 MPa for St-Sulp.

In the case of extrusion, for soil with a sufficient clay content, combined with HMP, it seems to be the forming process that could lead to the highest compressive strength but it appears that it is not well suited to all kinds of earths (for example, the soil from Redon). Extrusion is leading to a maximum compressive strength of 11.5 MPa in the best case for St-Sulp-HMP and of 3.2 MPa for kaolin-HMP.

6 CONCLUSIONS

In this paper, we have reviewed different forming processes for different sorts of soil in order to optimize the processing of raw earth's blocks with the best mechanical properties systematically. First of all we have adapted the rheology of each soil with and without the addition of dispersant to each sort of forming process.

Then we have highlighted the fact that the increase of the compaction effort, and the addition of dispersant and vibration, for compacted (or vibro-compacted if vibration is added) samples is increasing significantly their mechanical characteristics: it allows to improve the compressive strength from 1.3 to 2.5 MPa in the best case for the kaolin based mortar, from 2.1 to 3.1 MPa or the earth from Redon and from 5 to 7.1 MPa or the earth from St-Sulpice-La-Forêt.

In the final part we have compared the four different process methods and it appears that both of extrusion and vibro-compaction could be good forming processes to guarantee an industrial processing of raw earth's blocks in compliance with modern standards without hydraulic binders. Indeed, both of these methods, allow to regularly aim for a minimum compressive strength of 2.5 MPa for all of the tested soils in this study, a good level of compressive strength for a structural material.

In some other developments, it could be interesting to produce more data following the same procedure, in order to confirm our statements. Moreover, in this study we are using Na-HMP as a dispersant which is a chemical and industrial product. Even if the content of Na-HMP is really low, it could be interesting to work on bio-based dispersants such as citric acid, tannins or oak seeds extract to replace Na-HMP. Finally this study is giving some key points to reach a good level of mechanical properties for a range of different soils, but it could be interesting to find some bio-based additions that could stabilize the earth blocks and protect them from the action of water such as alginate, tannins, oak seed extract, cellulosic glue, casein, linseed oil.

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