Auroville Earth Institute
UNESCO CHAIR EARTHEN ARCHITECTURE

POURED EARTH CONCRETE (PEC) RESEARCH

FINAL SYNTHESIS REPORT

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SUMMARY

This report is about a five months (from May to September) research on an Earth technique for construction: the Poured Earth Concrete. Leo BOULICOT (4th year student in material sciences engineering - Polytech' Montpellier - France) started the research during the first month by some documentaries research: reading about previous works done by other researchers here in Auroville Earth Institute, reading documents and reports to learn more about usual concrete and the Earth material. Then, Theo VINCESLAS (4th year student in civil engineering - Polytech' Nantes - France) arrived at the end of this first step and they started to work together to find ideas and build the research process.

Here is an extract of the AVEI research plan for PEC:

GENERAL AIM

Continue from the last results obtained by Clémentine and further apply the research as indicated in her report "2014 01 06 - Next steps and summary of the research".
Increase the proportion Soil/Aggregates but still maintaining the following mechanical characteristics:

- *Strength: minimum 7 MPa dry and 4 MPa wet*
- *Water absorption: less than 10* %
- *Shrinkage: less than 0.1* %

Clémentine arrived at satisfactory results with 35 % soil. It would be good to achieve 50% soil and 50% aggregates (Ratios of sand and various gravel size will have to be defined).

FUTURE AVEI RESEARCH DIRECTIONS

Note that the following items are not necessarily sequential.

- *Conduct tests on samples (cubes or cylinders) for water absorption and compressive strength (dry and wet)*
- *Cast 3 walls with the same specification as above but with a more clayey soil (From Mangalam).*
- *Cast 3 walls of 10m long each: 1 with the red soil, 1 with the soil from Mangalam and 1 with 50% of both soils.*
- *Continue with the research on reinforced poured earth concrete with steel and bamboo.*
- *Find a plasticiser which works well (preferably natural).*

Regarding the general aim, compressive strength, water absorption and shrinkage goals were reached. The representativeness and the accuracy of produced results can still be discussed, but from the 35 tested mixes, 8 of them reached the wanted properties according to our way to test them (within these 8 successful mixes, some of them contain only 40% of soil).

For the research directions, compressive strength test and water absorption test were done on cylinders, while the shrinkage test was done on beams (which are supposed to be tested in flexion soon).
Only two walls were casted. Both of them have 40% of soil, one is only red soil and the other contain red and Mangalam soil.
We did not find the time to work on reinforced poured earth concrete, but knowing that good proportions were found research on this topic can start. As for reinforced poured earth concrete, we did not work enough on plasticizers, but it will be also easier know with the results we obtained.

TABLE OF CONTENTS

TABLE OF GRAPHS

TABLE OF PICTURES

TABLE OF TABLES

1. INTRODUCTION

Earth is a wide spread material. Since millennia, humans used it for many different applications, and one of the most famous is the construction knowing that they are still resisting. Nowadays, according to American energy department, 50% of people in the world are living in raw earth buildings. Some of old and famous buildings like the Great Wall of China are done with this material because it is local and cheap to use, but it has also a very good durability.

However, if lot of techniques using this material (like rammed earth or adobe) are well known and used since thousands years, the poured earth concrete is not well developed nowadays. This technique is based on classical poured concrete but adding an important amount of soil. Its aim is to save construction time using an environmentally friendly material.

Indeed, earth can be taken directly on the building site, using the levelling earth. Moreover, earth is a natural material perfectly recyclable after using, even if it is stabilized with lime or cement. This statement is true especially if the percentage of stabilizer used is decreased to the minimum in order to decrease the environmental impact induced by cement and lime making.

Finally, this material is really cost effective because it is wide-spread and also because the preparation does not require neither a lot of energy nor a lot of transformation process. Other advantages can be listed as its insulation capacity, its design interests, its healthy properties and many others.

The aim of this research is to design a mix which uses 50% of soil, reaching at least 4MPa wet and 7MPa dry compressive strength, with less than 0.1% shrinkage and less than 10% water absorption. To reach these goals, first studies were done about protocols definitions and materials characterization and then, mixes were designed and tested (see \\192.168.0.1\Research Projects\R&D 04 Poured Earth\06 Reports\2014 Léo Boulicot & Théo Vinceslas\Next steps\Summary works already done.docx).

Poured Earth Concrete research started in 2011, and the beginning seemed to be quite hard. It is actually the first time in 2014 that two students are working together as a team on this project, and it seems to be highly beneficial for the research progress.

This report starts by a review on what was found during the first step of documentation and what ideas it brought to us. Then, the research process will be detailed, explaining methodology, calculation and techniques used for each step. To finish, two different parts will present the results: one for the preliminary tests (necessary for designing different mixes), and the other for the results on each mixes including comparison between them.

2. PREVIOUS WORKS – THEORETICAL STUDIES

Because earth is an ancestral construction material, it is mostly used through non mechanised and non conventional processes. However, in order to save time and spread the earth as a building material in the current society, a new technique is being developed: the poured earth concrete. This technique is studied since a few years (around 5 years in the Auroville Earth Institute) in different countries like USA, France and South Korea. Considering that the soil is a mix of different size of pebbles, gravels, sands, silts and different clays (1), we can compare the soil to the usual concrete (which gradation is done artificially) where clays are the binder. The question is to know how to maintain the needed structure and the needed strength through the time, particularly against water. For that, stabilizers are used as cement or lime like in the usual concrete. These stabilizers permit to maintain the skeleton compound of aggregates and resist to humidity, erosion, the load apply on, animals and moistures degradations and other kind of attacks.

Compared with other techniques already used with earth, this one would permit to build faster, with a lot of different shapes while increasing the possibilities for the Institute and later for other builders.

We have to underline that this research is done in order to be applied directly onsite. Moreover, because it is for buildings, quantities are not given in milligrams but in kg and the accuracy cannot be better than the percent because of the tools used here. However, for some previous characterization done in the laboratory, the accuracy and measures are done more properly, closer from studies we have the habit to do in university's laboratories.

This report is about the work of the forth students team working on this subject. So the first step was to study what have been done by the others in order to stay in a continuous research process. Leo Boulicot is a material sciences student while Theo Vinceslas is a civil engineering student, which means that we had to complete our knowledge by some explanation from one to the other (about concrete behaviour in one side and chemical reactions on the other, for example). Finally, because the poured earth concrete must be done with a high amount of soil, we had to find documentation about this material, new for us, understanding the studies done in majority by geologists.

Definitions: in this report,

- **Aggregates** are soils and different size of gravels and pebbles added in the mix, main components of the earth concrete.
- **Additives** are cement, lime and other components added in small quantities.
- **Dry mix** is the mix without water (aggregates and additives).

2.1 SOIL DEFINITION

A soil is a "superficial layer of earth's crust in regard to its constitution or its productive quality", translation from (2). The constitution of a soil is the most important parameter in order to build with it. Soils studied here are the local soil of Auroville (called "red soil" in this report) and the local soil of Mangalam, where the new building for AVEI School is planned.

In order to use this soil, we need to characterize it physically and chemically.

The physical characterization corresponds to determine the gradation of this soil (gradation curve as described in (3)) and its composition in term of main constituents (clay, silts, sand, gravels and pebbles). This characterization is done here by:

- Sieving for the big aggregates (pebbles, gravels and sands)

Aggregate	Size (mm)	Percentage
gravels	Up to 4	0
pebbles	4-2	3.4
Coarse sands	2-0.212	53.8
thin sands	0.212-0.075	37.0
Silt+clay	Less than 0.075	5.8

Table 1: Aggregates in red soil, according to (4)

According to table 1 (size are given according to sieves used and not real size of each aggregates), (5) and (4), the red soil is mostly sandy, with thin sands. More tests will be done to check its composition and determine the composition of the Mangalam soil.

- Hydrometer test for the thin aggregates (silts, clays).

The reliability of those tests is debatable (comparison with results obtained by sensitive tests (5)).

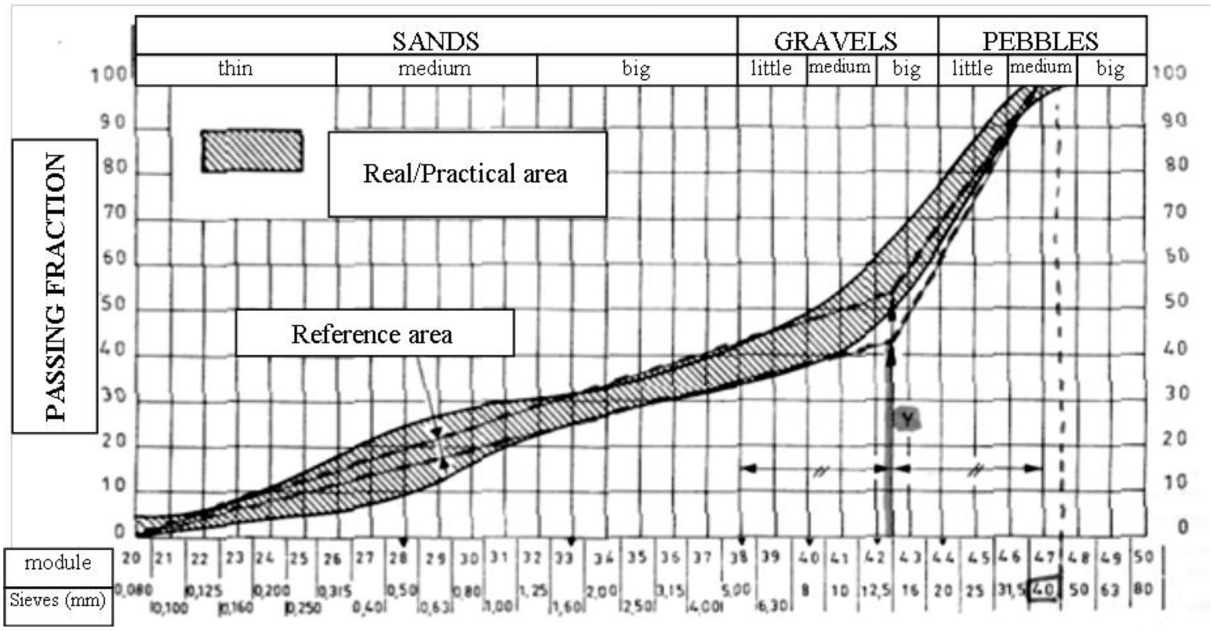
Another parameter important to know for a soil is its density. The specific density is more accurate and independent of the state of the soil, but the bulk density is the one used onsite. Later parameter was already determined (5).

- Red soil bulk density : 1.23kg/m^3
- Mangalam soil bulk density: 1.27kg/m^3

The chemical characterization cannot be done in the AVEI's laboratory, knowing that not any tool is available. Nevertheless, it is an important parameter because it also affects the Earth Concrete's behaviour.

2.2 GRADATION TOOL

This tool, a basic excel sheet (6), was designed by another student, J. Cochet, in order to be able to predict the gradation curve of an aggregate mix, choosing volume percentage of each aggregate while knowing their gradation. The DREUX and GORISSE Method (7), developed for usual concrete, permits to determine gradation curves which induce the highest densities (see picture 2 below). Therefore, fitting the gradation curve modelled with this tool and the "real and practical area" defined by (7), best densities should be modelled.



Picture 1: Dreux-Gorisse ideal gradation for concrete wall application

According to (6), this tool is not accurate but permits to have an idea about proportions of aggregates added in the mix. The real best specific density has to be determined with the corresponding protocol (see part 5 p.32, densities results).

In order to fit as well as possible to this method and knowing that using bigger aggregates permits to increase the compressive strength (4), the decision was taken to use 2 inches aggregates (~5cm). Moreover, according to a theory used to model the best compactedness (1), mixes without middle-size aggregates are tried, which should permit to improve the workability without decreasing the specific density.

2.3 PROPORTIONS

2.3.1 Soil

The aim of this study is to design a concrete based on 50% of earth. Knowing that good results were found by the previous student (8) for mixes with 7,5% of cement and between 30% and 40% of red soil, the next step is to find a good one with 50% of soil. Characteristics asked (compressive strength particularly) were increased since the last internship in order to compensate possible errors done by researchers, workers and other non-human parameters.

Finally, two percentage of soil are tested: 40% and 50%. The red soil seems to have a good behaviour (8) as building material. However, this percentage seems to not give good results with Mangalam soil only (8), so a mix with red and Mangalam soil is designed in order to decrease the effect of Mangalam soil.

2.3.2 Cement

The cement is the binder in usual concrete. In earth concrete, it is also a component which permits to stabilize clays against the water. Indeed, heavy rains in this area imply this treatment in order to decrease the effect of water on the behaviour of the building (5).

Compared with previous works, increasing the amount of soil in the mix and increasing the compressive strength which has to be reached, it seems to be important to increase the amount of cement in the mix. Moreover, good results have to be found quickly in order to begin to build one-scale constructions. 9% of cement, as calculated below (in part 2.3.3 p.20), is set. Additional studies could be done if results show a really high compressive strength, in order to optimize additive quantities to decrease their use.

2.3.3 Additives

In order to reach the properties set, different additives are tested. Each one are added in a specific goal, developed below.

Because we want to test the effect of many different additives, not more than 3 different proportions are tested for each one: a low value, a high value and a medium one. With these values, we want to determine a tendency, in order to determine the ideal proportion in the future.

2.3.4 Water

According to (4), (8) and (9), the minimum percentage of water is around 11% to have a good ability to be vibrated in order to avoid bubbles in samples keeping a low quantity of water in order to decrease shrinkage while drying. In first approximation, 10% are slowly added in the dry mix, in order to stop its addition if the mix is wet enough. Additional water will be added and counted if needed. Two techniques are used to determine the good quantity of water: the feeling of the mason, checked with a slump test (see part 2.3.4, p.21).

The percentage is calculated as for additives (see part 2.3.3 p.20):

2.4 GOALS OF ADDITIVES USE

Additives are chemicals or organic materials added in small quantities to noticeably modify one or many properties in the concrete behaviour while pouring it or after drying. The difficulty is to find an additive meeting these expectations without decreasing others properties. The choice was done to try many different of them in order to determine their effects as a wide range research.

2.4.1 Tests done by previous students

Many tests were done by C. Browne (8), J. Cochet (4) and A. Lehuede (9) on additives, without really reach set properties. The use of plasticizers, in order to decrease the amount of water needed to pour the concrete was particularly investigated. Using a good plasticizer should permit to decrease the shrinkage while drying, which induce cracks. These cracks are part of the structure's weakening (10).

The plasticizers tested were:

- Washing powder. As an anticoagulant (used in TP of ceramic), soaps are good plasticizer, a property shown in (9). However, according to the same document, the compressive strength decreases dramatically using washing powder, inducing an impossibility of use.
- Soapnut. It is a common nut use in this area as soap after been soaked in water. The same
- Concrete superplasticizers. Chemicals from the concrete industry, designed to react with the cement, it seems to have a good effect in term of workability but not as remarkable as for classic concrete as there is less cement in the earth concrete mix. However, to stay in an eco-friendly continuity, this additive was not tried anymore

Other binders, reacting as cement or lime were tested as well, to reduce their quantities in mixes. But local lime, “Maxeh additive”, rice fly husk or flying ash did not give really good results. According to (9), best compressive strengths obtained were around 2MPa[1].

However, tests done by Clementine in (8) with a mix of lime+cement as stabilizers were promising. Indeed, cement reacts with sands and lime reacts more with clays threw a pozzolanic reaction (5). A combination of these effects, which have to be proved, could permit to maximize the efficiency of each one.

2.4.2 Coconut fibers

In order to avoid the shrinkage, a well spread technique used with earth techniques is the use of fibers (11). Fibers, creating a matrix not as water-dependant as clay can be, permit to maintain the dimension set by the mould. Ideally, they could also reinforce the concrete against tensile strengths, here not studied, but which are important parameters for any kind of construction applications (12). Those fibers are used as they are cheap and completely ecological material, with great coconut trees plantations in this area.

2.4.3 Lime and Alum Paste and Homeopathic Mix of Lime and Alum

According to (13), addition of alum with lime produces ammonia, a waterproof agent. This effect will be checked threw two types of experimentations:

- Mixes with additional lime, used as binder as it is without alum (LAP).
- Mixes with exact proportions of lime and alum in order to produce as ammonia as possible, but without lime as binder (HOMLA).

For that, chosen quantities are determined according to (13). However, because of some observations done while making mixing, tests on solubility and reactivity were designed and done (14).

[1] This low compressive strength could also be explained by the aggregate proportions, closer to CSEB (compressed stabilized earth blocks) than usual concrete.

2.4.4 Geopolymers

Geopolymers were defined by J. DAVIDOVITS, a French archaeologist, in 1978. A theory of their use for the building of pyramids in Egypt is currently discussed by many archaeologists and scientifics. A geopolymer is a stone done with soil, aggregates and others additives. Threw successive chemical reactions (parallel can be done with organic polymers), the atoms network of aggregates is modified in order to bind them, making a new network, integrating all atoms in the final network of the stone obtained at the end. While this material is new, chemical process is not perfectly known but some propositions are done by J. DAVIDOVITS (15).

According to a document shared with the institute (16), mixes were designed in order to test effect of caustic soda on the different components of our Earth Concrete: chemical reactions of caustic soda with cement, lime and clay were theoretically studied (a complete report was written before the casting about theoretical researches on geopolymers (17)). These tests are based on a few information and many hypotheses were done (see appendix 7, p.50). But comparison will be possible with mixes without caustic soda knowing that proportions of aggregates are the same.

2.5 TESTS ON MIXES

In order to determine the set properties, different tests were designed, most of them were already well known, but some modifications were added in order to fit with the possibilities of the Institute.

2.5.1 Slump test

The slump test is a test done onsite, while casting the structure, applied basically for usual concrete. It permits to determine the consistency of a mix, before being poured, in order to reach the property of workability set depending on the technique used. According to previous researches done in the Institute (8), (4), the mix must have the possibility to be vibrated easily with a vibrating machine. The use of this machine permits to decrease the amount of water in the mix while avoiding air bubbles inside and reorganising as well as possible the aggregates.

2.5.2 Sample representativeness - sizes

One of the questions, not accurately solved, was to determine the size of samples, according to components used. Indeed, using 2 inches aggregates, usual sizes of samples were not big enough to test representatively the mix. So, finally, we considered that bigger samples (than standard ones) were more adapted to our researches than usual ones, even if the comparison with standardized results is more questionable. According to (18) (which gives the actual standards in terms of compressive strength tests), the height of sample must be two times the width. Under one time, friction forces can induce an overestimation of the compressive strength. Meanwhile, over two times, there are some buckling risks which can bring us to an underestimation of the compressive strength (Dimensions are in part 3.7.3, p24) The representativeness of these kinds of samples is actually still in research.

2.5.3 Shrinkage

The shrinkage is due to the behaviour of clays, while drying. Indeed, putting water in a clayey mix, it tends to swell. Because of electromagnetic interaction between clays layers and polar water molecules (19), particles of clay are separated by a layer of water. Drying, the water tends to be evaporated and clays particles tend to go near one of each other. At a bigger scale, samples tend to shrink. If the shrink is too important, cracks appear weakening the structure, knowing that the cohesion decrease as well as loaded surfaces.

This test is the harder to design. Indeed, the shrinkage set, 0.1% is a low percentage, and the main problem is to find a way to have an accurate measure enough with tools used and protocol done to measure this low value. Be able to measure less than 1mm on a sample of 1m length with a good accuracy remains an issue with tools used. But a protocol was proposed and measures were done.

2.5.4 Water absorption

The water absorption is the ability of a mix, after being dried, to catch water in its pores. Compared with the usual concrete, earth concrete is less dense, has more bubbles and is not waterproof. Indeed, interactions between thin particles and water induce an important absorption of water. Even if additives used, as cement, should stabilize the earth in the mix, they are not as effective as in usual concrete and the dry mix as a good ability to attract humidity in the air. We can compare this effect with one of the plaster. It is a good property for the healthy aspect of a house, but it induces a weakening of the structure. Water acting as a lubricant with aggregates but also destroying bounds between them because of its polarity, a big amount of water is an issue for a structure. Tests are done in worse conditions that means when samples are totally wet, according to tests implemented by CRATerre (20). Indeed, heavy rains during monsoons in this area, could damage the structure in case of important water absorption.

2.5.5 Compressive strength

The compressive strength test is the most used test to determine the main property of a concrete, the compressive strength. Knowing that for a building material, as earth concrete, strains are mainly put from the top to the bottom, the compressive strength is essential. There are other strengths (traction ore bending strengths due to the buckling for example) but less important, in first approximation, considering dimensions of applied structures. As for tensile strength or bending strength practiced during practical courses (21), a load is applied by a machine in order to break the sample, to know its behaviour under an increasing pressure. Samples have to have parallels faces, known dimensions and a shape which fits with the machine.

To characterize mixes, tests are done on three samples and an average is done according to previous works (4) (9) (8). The behaviour after being dried and after being soaked is tested in order to determine the weaker condition.

Based on these works, different steps were defined in order to reach given goals: first of all characterize used soils then, define the best aggregate mix and finally study the effect of different additives.

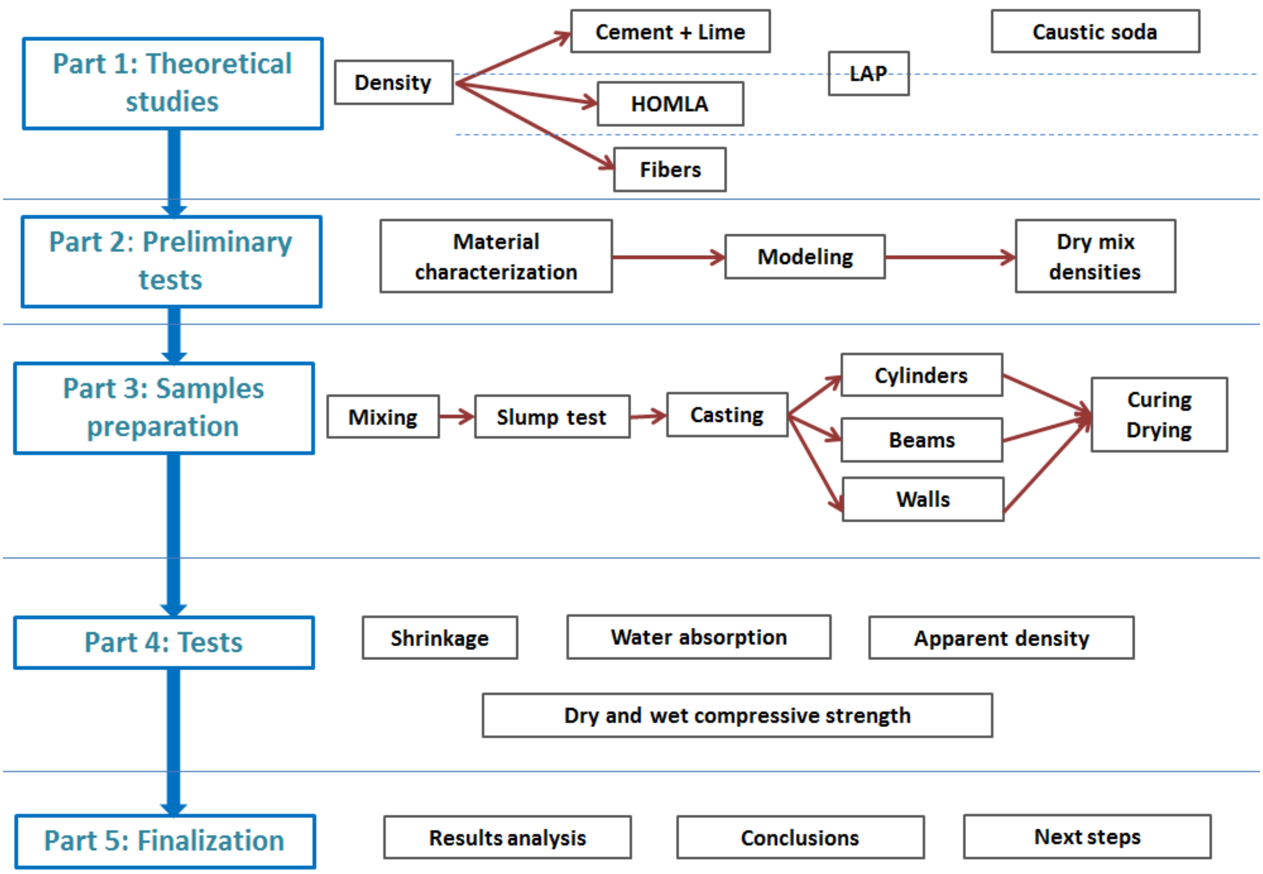
In order to reach these goals, protocols already defined by different organisms were used. However, in order to adapt protocols with tools available in the Institute, some modifications have been made. Protocols are given hereafter or in appendixes part in order to understand as well as possible different steps followed.

3. RESEARCH STEPS AND TECHNIQUES USED

3.1 RESEARCH PROCESS

After the studies of previous works, in order to have a clear idea of what have to be done, it was needed to think about the different steps the research have to go through:

- First of all, a theoretical study of each and every material that is going to be used is needed. The aim was to find some of their characteristics, like their density to also be able to find in which quantity they have to be used.
- In a second part, the modelling of these quantities (here particularly for the dry mix, including only aggregates) was done in order to find the good mix. This modelling was done on the computer while its verification was done by real application.
- The third step is about realisation: make the different samples for every mix, and then follow the process of curing and drying.
- Fourthly, it is about doing the different planned tests.
- Finally, to conclude the research process, all the produced data has to be exploited to get the results, build conclusions and interpretations which will be used to think about the next steps of the general research.



Picture 2: Research process chart.

3.2 SOILS DEFINITION

3.2.1 Big particles

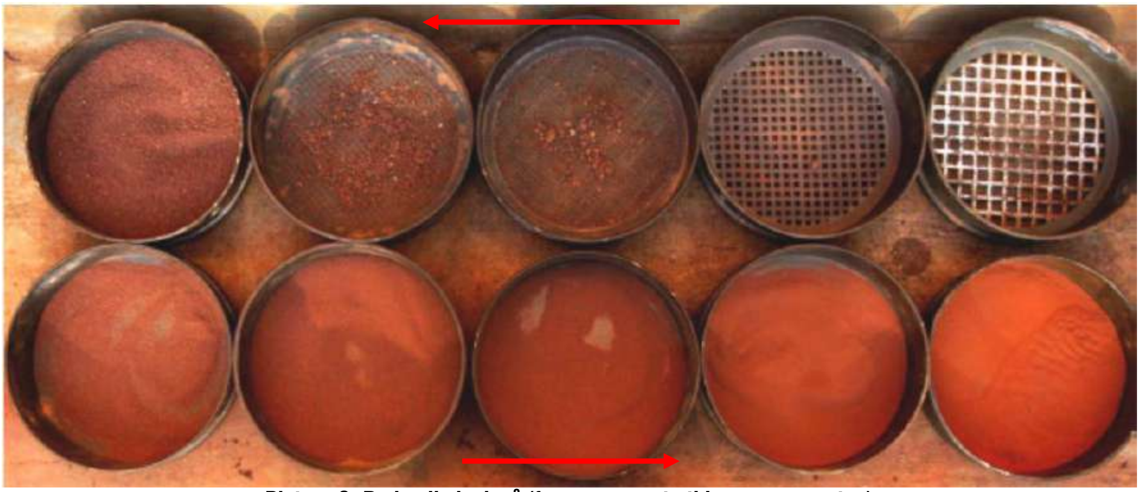
An adequate amount of mixture has to be used to determine more accurately the exact gradation, according to a statistic principle. Thus the mass of the test sample depends on the size of the coarsest elements it contains. The needed mass will be calculated before sieving as following CRATerre protocol (3):

$$200 * D < M_{T1} < 600 * D$$

M_{T1}: Total mass of the sample dried (g)
D: Diameter of the coarsest aggregate (mm)

Then, the sieving[2] will be done:

- Dry the sample during approximately one night in an oven at 90°C.
- Weigh the total sample dried (M_{T1}).
- Weigh empty sieves separately (M_{Ei}).
- The soil is sieved manually, using sieves one by one from the biggest to the thinnest, shaking it during 1min, checking if the retained fraction does not change more than 1%. Mesh sizes of theses sieves are, in mm: 40; 20; 10; 0.5; 0.212; 0.106; 0.075.
- Weigh different sieves and the corresponding size of aggregate inside (M_{Fi}).
- Total particles mass for each size is deduced.



Picture 3: Red soil sieving[3] (from coarser to thinner aggregates)

Remark: according to the accuracy of the tool used (scale 2g accurate), a wet sieving would have not be useful knowing that the washed fraction would have weigh less than 2g.
Aggregates passing 0.106mm mesh will be used for the sedimentation test. (22)

[2] coming from CRATerre protocol (3), modified in order to use it with the tool in AVEI laboratory
[3] Image taken by Jerome in (4), visually same results were obtained.

1) *Mass percentage of each aggregate size:*

$$P_{Ai} = 100 * \left(\frac{M_{Fi} - M_{Ei}}{M_{T1}}\right)$$

P_{Ai}: Mass percentage of aggregate size corresponding with the sieve i (%)
M_{Fi}: Mass of the full sieve (g)
M_{Ei}: Mass of the empty sieve (g)
i: range of the sieve

2) *Mass percentage of passing fraction* (3)*:*

$$P_{pfi} = 100 * \left(1 - \sum_{i} P_{Ai}\right)$$

P_{pf}: Mass percentage of passing fraction i (%)

3.2.2 Thin particles

- **HYDROMETER PRINCIPLE according to CRATerre and ASTM** (20), (22)

Grains of soil of differing diameters, placed in homogeneous suspension in a standing liquid, sediment, or "fall", with different speeds according to their diameters. In the course of this sedimentation, the specific density of the initially homogenous mixture will increase from the top to the bottom as time passes. By measuring times and specific densities and by using Stokes' law, we can obtain a spread of the diameters of the grains of soil which are assumed to be spherical (although they are not generally so).

Stokes' law calculates the speed of fall of the spherical grain of soil of equivalent diameter in a certain liquid.

This speed depends on the specific gravity of the grain, and on the viscosity of the liquid, which depends on the temperature and on gravity acceleration.

The results are read using a hydrometer. Correction factors will therefore need to be introduced to allow for the hydrometer, the composition of the liquid, the temperature and if appropriate the specific density of the grains. Here, without knowing the grains specific density, we will consider that all particles have the same specific density, $2.65 g.cm^{-3}$. The other correction factors are determined using a control sample, without any particles inside.

An important starting point of the principle of the test consists in putting the sample in homogenous suspension. In order to be sure that all the fines are broken down, the sample will be placed in a liquid containing a dispersal agent.

➢ **HYDROMETER PROTOCOL** (20)

This protocol follows a modified ASTM protocol in order to use tools available in AVEI laboratory (22).

1) Sodium hexametaphosphate ($Na_6(PO_3)_6$) solution preparation

Picture 4: Preparing the sodium hexametaphosphate solution

Distilled water used only. The preparation of one litre is around 30min long, as shown on picture 4, a few basic tools are needed.

The dispersant agent used is the sodium hexametaphosphate, $Na_6(PO_3)_6$, with concentration of 50g/L. Preparation of this solution:

- Place 50 g of sodium hexametaphosphate and 0.5 litres of distilled water in a glass recipient.
- Heat, stirring until the powder has dissolved completely. Avoid heating over 50°C.
- When the powder has dissolved completely, top up using distilled water to 1 litre.
- Keep the dispersing agent in a sealed bottle labelled with the date of manufacture.
- Do not keep the solution for more than one month.

Only 1L beakers are available, so the quantity is not as accurate as obtained with a volumetric flask. Scale used here is 0.01g accurate.

2) Soil solution preparation

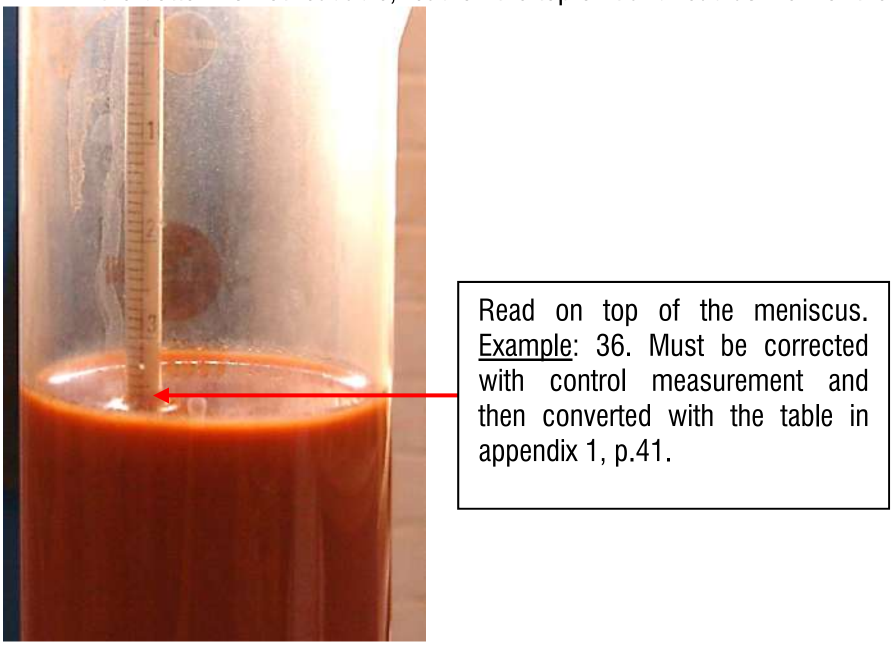
- The fraction under 0.106 mm[4], retrieved after sieving of the soil sample is dried during one night at 105°C.
- Weight 50 g of material passing 0.106mm for a 1 litre cylinder.
- Immerse completely this sample for 12 to 15 hours in a vessel containing 180 cm^3 of dispersant agent (sodium hexametaphosphate) solution already prepared for a 1 litre cylinder. Cover it to avoid additional dust.
- Stir the suspension mechanically during 10 minutes at 6000r.p.m.
- Pour the dispersed suspension into the 1 litre cylinder and thoroughly rinse the vessel and the stirrer. Using the dispersant agent solution, top up to exactly 1 litre.

A control sample will be prepared, with the same quantity of dispersing agent (i.e. 40g/L concentration). This sample allows the reading correction. Indeed, the reading depends on size of meniscus, temperature and dispersing agent.

[4] The test is carried out from ø < 0.1 so that the results can be compared with those of particle size distribution analysis by sieving which is carried out from diameter up to 0.075 mm

3) Hydrometer measurement

- Before carrying out the test, check that the stem of the hydrometer is perfectly clean. Once the test is in progress, never pick up the hydrometer other than by the upper tip of the stem.
- The solution with particles in the 1L cylinder is mixed vigorously (by hand) and the chronometer is started. The mix continues during one minute and then, the hydrometer is inserted.
- The control reading is done for each measure in solution in order to avoid errors due to the meniscus, the temperature and the specific density of the dispersant agent.
- Measures are done reading, on the hydrometer, the sink of latter on the bottom of the meniscus. If the bottom is not readable, read on the top of it and read as well for the control reading.



Picture 5: Hydrometer "R" reading

- Measures are done at different times: 1.5, 2, 5, 15, 30, 60, 250, and 1440 min.
- Until the 2nd measure, let the hydrometer in the solution. After the 2nd, remove it, clean it and read the control measurement. Do this process for each measure.

4) Diameter of concerned particles, at t time, is calculated as following:

$$D = K\sqrt{\frac{L}{t}}$$

D: Diameter of particles at time t (mm)
K: constant depending on the temperature of the suspension and the specific gravity of the soil particles. Values of K for a range of temperatures and specific gravities are given in appendix 1, p.41. Here the specific gravity (or specific density) is chosen as 2.65g/cm^3. The value of K does not change for a series of readings constituting a test, while values of R and t do vary. A linear extrapolation is done for value higher than 30°C.
L: Is the effective depth known with the R reading. The equivalence relation is given in appendix 1, p41.

5) *Percentage of this size of particles in the solution:*

$$P_{IS} = \frac{(R - C) * 100}{M_{T2}}$$

P_{IS}: mass percentage of grains for the various equivalent diameters (%)
R: Reading (specific density of the solution at time t) (g/cm^3)
C: Correction reading, read into the control sample at the time t (g/cm^3)
M_{T2}: Total mass of the sample (g)

After determine the composition, in term of size of particles, these data have to be used in the gradation tool in order to reach the best specific density for the aggregates mix. Additional observations are done after 1month sedimentation, see appendix 2 p.42

3.3 DENSITIES

In order to complete the physical description of the soil, two densities are calculated: the bulk density and the specific density.

3.3.1 Specific density

It is the mass of a material by volume unit. In a homogeneous material, it is an intrinsic property. Protocol followed is given in appendix 3, p.43.

3.3.2 Bulk density

It is the density used to characterize a fractioned sample. The visible volume (included matter, porosity and spaces between grains) is used instead of the real volume (corresponding to the volume of full matter). Protocol followed is given in appendix 4, p.44.

3.3.3 Mixes specific density

Specific densities of different mixes done are measured as above (see appendix 3, p.43) after having mixed all the aggregates (without any additives) with defined proportions.

In order to compare best densities obtained by modelling (see part 1.2, p.9), specific densities, which are more accurate were measured.

3.3.4 Samples apparent densities

Apparent densities of samples are calculated as:

$$\rho_{sample} = \frac{m_{sample}}{V_{sample}}$$

m_{sample}: mass (g) of the sample, after drying under the sun (23)
V_{sample}: volume of the sample (cm^3)
$\square_{sample}$: mass of the sample (g/cm^3 or kg/m^3)

3.4 GRADATION TOOL

The first version of this tool (6) has been modified in order to add different components in mixes, like Mangalam soil and 2inches aggregates, after having done all studies on these aggregates. Modifying percentage of each aggregate, the use of this software permits to model, calculating automatically and then drawing gradation curves obtained for the designed mix. Trying to make this curve fit with the zone defined by (7) should permit to increase the mix specific density. Six different mixes are designed for each proportion of soil, tested (with the protocol defined part 2.2.1 p.19) and the one with the higher specific density is chosen.

3.5 ADDITIVES

Quantities of additives are added following this calculation:

$$\%add = \frac{m_{add}}{m_{add} * m_{agg}}$$

%add: percentage of the additive added
m_{add}*: mass of the additive added (kg)*
m_{agg}*: mass of aggregates added (kg)*
Remark: if quantities are determined differently, it is described in the corresponding part.

3.6 MIXES

Different compositions are tested in order to determine the effect on different additives depending on the used quantities. Quantities are given according to mixes done, 1% rounded.

In order to follow the technique used until now to calculate, choosing percentages, volumes added onsite and final real percentages in the mix; a report has been written and followed (24). Indeed, if theoretical studies are done by weight to be more accurate, volumes are used onsite to prepare quantities used. So the determination of the bulk density of each material is really important.

Refer to appendix 5, p.45 to have more details on materials used.

One of the main theoretical studies was to write protocols to make and test samples in order to have a good repeatability. Different steps are described hereafter.

3.6.1 Hand mixing

Because the Institute does not have any mixing machine, mixes are hand done, using commons tools.
Tools used:

- Shovel, hoe, crowbar, trowels, smoother, ruler, scales, clamps, formworks, pliers,
- Recipients
    - Wheelbarrows of 50L, 75L, 100L, 200L
    - Buckets of 11L, 15L
    - Recipients of 1L, 2L
    - Barrels of 100L, 200L
    - pan
- Security equipments: boots, glasses, waterproof gloves, gasmasks, dust masks, waterproof jacket and pants.

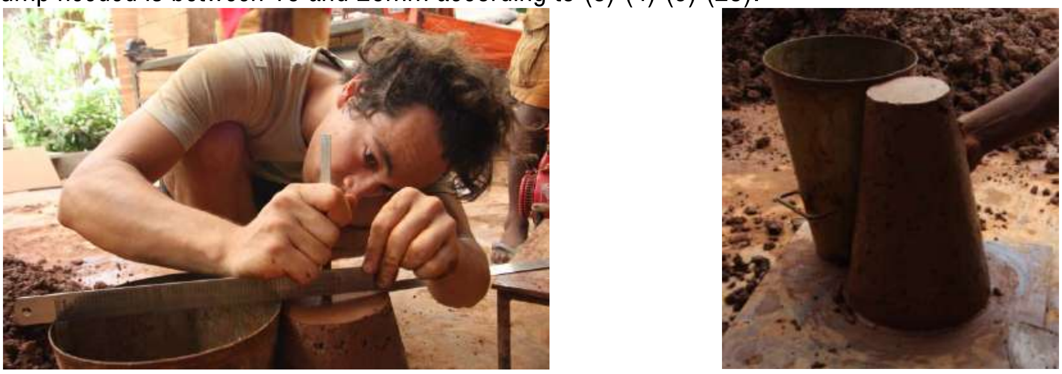
Mixing steps (13) refer to picture 6:

1) Preparation of all quantities needed, given in litre (aggregates, additives and water).
2) Thinnest particles (i.e. soils, cement and lime) are mixed twice together on the ground (cement slab).
3) Gravels and pebbles are added and mixed.
4) Half of the water added, mixing again.
5) Other half of water is added little by little, mixing again.
6) Additional water is added if needed, mixing again.

Picture 6: Steps to do a mix by hand

3.6.2 Slump test

The protocol comes from (8). Usual Abraham's cone (with normalised dimensions as in standardised European protocol NFP 18-451) is used. It is greased, and then full by layers of around 15cm, each one rammed with a bar of 1.6cm diameter. The top surface is then smoothed and the mould cone is removed and placed close to the concrete cone and the slump is measured, as shown on picture 7. The slump needed is between 10 and 20mm according to (8) (4) (9) (25).



Picture 7: slump measure and tools used

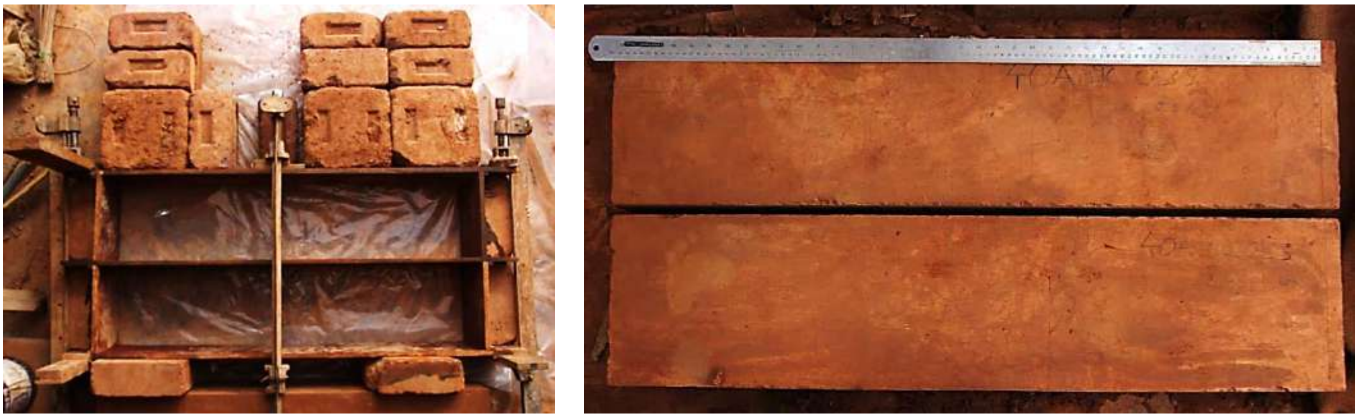
3.7 TESTS ON SAMPLES

Samples are poured, when the consistency fits with the one expected. The earth concrete is poured into greased moulds, by layers of approximately 10cm. Each layer is vibrated with a vibrating machine (needle type) until the mix is compact, avoiding bubbles and holes. Then, surfaces are level up, smoothed with a trowel and a wood smoother. Moulds are removed at least 3 hours later.

Samples are then cured during 28 days in order to maintain humidity in the sample which permits to make reacts additives, particularly cement and lime. Indeed, temperatures in this area imply a fast drying, weakening the concrete (this technique is also used for usual concrete) Cement stabilized samples are then dried during 10 days under the sun in order to remove the residual water while lime are dried 28 days. Lime need to be dried longer because it reacts slower than cement, needing to tap CO_2 from the air. Studies (26) show that lime continues to harden more than 6 months after being mixed with water. While drying, samples are protected against water adding a block and a plastic sheet under their base and a canvas cover is placed during night and rains.

3.7.1 Shrinkage

Shrinkage is measured with long samples, called here beams as shown on picture 8. Dimensions of wooden formworks are: length 102cm, width 24cm and height 19cm.



Picture 8: Shrinkage moulds, samples and measurement

After smoothing the surface, a 1m ruler, with 0.5mm accuracy is used in order to trace a thin line, 1000.0mm far from one of the extremity. Two samples are poured for each mix.

In order to see the evolution of shrinkage through the time, measures are done after 7, 14, 28 days of curing and 7 (for cement stabilized only mixes) or 28 days (when there is lime into the mix) of drying. 3 measures are done for each beam, in order to do an average and also to show that the shrinkage is inhomogeneous.
Measures are done as shown on picture 9, reading the distance between the line done and the beam's extremity.

Picture 9: shrinkage measurement

Finally, the shrinkage test was done on the smoothed surface only, which may be not as representative as we should do. On another hand, the space to keep these samples out of the rain was not big enough to let space between all the beams, so it was actually the only solution.

Shrinkage (%) is calculated as:

$$shrinkage = \frac{100 * length_d}{initial\ length}$$

$length_d$: length on day d (mm)
initial length: length between the line and the beam's extremity, here 1000 (mm)

3.7.2 Water absorption

Samples used for this test are the same as for compressive strength (see part 3.7.3 p.24).

After being dried under the sun (the present oven in the AVEI laboratory is not big enough to get several samples inside), samples are considered without any water (23).They are weighted and soaked into water during 48 hours (A test was done, weighing the samples several times while they are soaked, to know when they are saturated). After 48 hours, they are considered fully wet, according to (3), (23). They are removed from the water and weighted in the following minute.

Water absorption (%) is calculated as:

$$water\ absorption = \frac{100 * (mass_{wet} - mass_{dry})}{mass_{dry}}$$

$mass_{wet}$: mass after soaking (kg)
$mass_{dry}$: mass after drying (kg)
Scale used: SEMSUNG, 10g accuracy, maximum load: 300kg.

3.7.3 Compressive strength

The compressive strength is measured on cylindrical samples (dimensions: 30.8cm diameter and 30.0 cm height), poured into plastic moulds.

The dry compressive strength is tested after 10 days of drying under the sun (because of the lack of an adapted oven). The wet compressive strength is tested just after having weighted the wet samples for the water absorption test (8).

The compressive machine used is a hydraulic machine, not able to measure deformation. The higher value of charge applied on sample's parallel surfaces is recorded and the compressive strength is automatically deduced (after complete dimensions of samples). The speed of loading is 5kN/s, deduced from the flow of the oil pumped (21). Compressed cardboard sheets are added in order to avoid surface defaults, keeping a good compressive strength's estimation. The advantage of this technique is to decrease shear stress in order to have the typical conical failure, proof of a sample's destruction mainly due to compressive stress[5].

Reminder: compressive strength (MPa) is calculated as:

$$compressive\ strength = \frac{10 * load}{area}$$

load: applied on parallel area by the machine, measured with an integrated sensor (kN)
area: determined with the diameter measure, measured with a calliper (cm^2)

[5] Because of the machine displacement limit, not any proper cone was observed. However, main cracks appeared in the middle and samples were more friable in the middle than on top surfaces. By using a hammer to hit the cracked parts, we finally observed the cone.

3.8 WALLS

Two one scale walls were poured in order to show the behaviour of poured earth concrete when used in real conditions. This experiment permits also to determine costs of this kind of walls.
Dimensions of a wall: 5.35m length, 24cm width, 1.20m height.

Foundations: same length, ~40cm width, ~40cm height material: rammed earth stabilized with 5% cement. 2 layers of blocks are used and one another is added on top, reinforced with steel and cement in order to avoid water infiltration from the soil and to give a good stay to the whole structure.
Composition:

- wall1: 41% red soil, 11% ½", 31% 1", 17% 2", 9% cement
- wall2: 25%red soil, 16% Mangalam soil, 11% ½", 31% 1", 17% 2", 9% cement, 3% lime.

Formworks usually used for rammed earth are used. Mixes are done as for samples, knowing quantities are more important, they are done in 6 different parts, each one based on 1 cement bag. The slump test wanted is more important (between 20 and 35cm) in order to prevent the drying while mixing knowing that mixes are done under the sun, directly on the earth and are quiet long to do because they were done by hand. Earth concrete is then poured in the formwork, by layers of 20cm and vibrated. The top surface is smoothed and the formwork is removed around 15h later (the next day). 6 cylindrical samples were also poured with the same mix, in order to determine its compressive strength. Walls are then cured and dried as for samples. Shrinkage is measured as on beams, but using a 10m ruler (1mm accurate) and the initial length is 5m.

All these protocols were used for this research. If most of them give accurate and usable results others are more debatable and corresponding conclusions have to be used with caution.

A complete report is written about the walls (27), giving more details about:

- Why these compositions has been chosen
- The available equipment for the formwork
- The mixing and pouring process
- The cost estimation
- All the observations and results

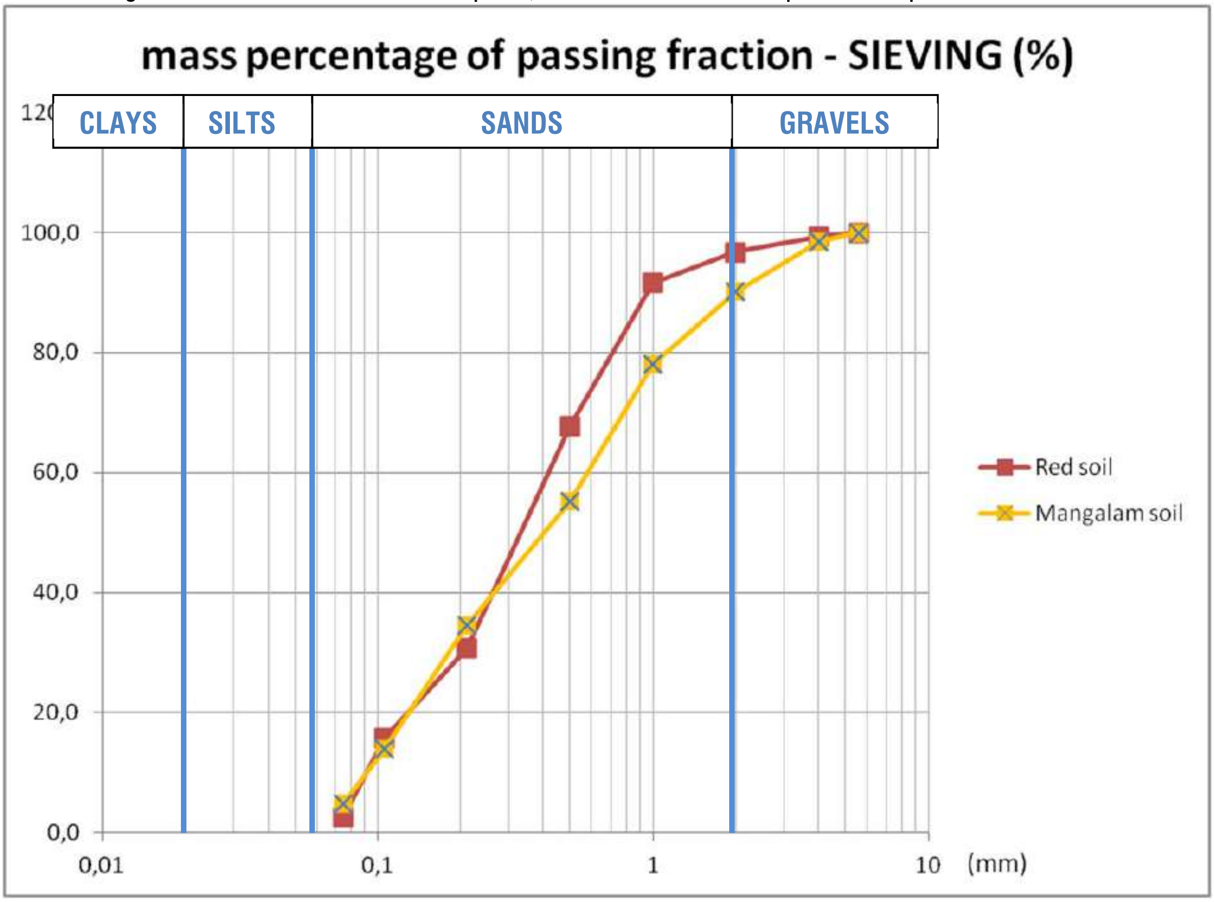
Here is the direct link to it: ..\Walls\Walls report.docx

4. RESULTS AND DISCUSSIONS ON PRELIMINARY TESTS

This first part of results will give the details about the output of preliminary tests and the casting, curing and drying parts.

4.1 SOIL GRADATION

Soil gradation test was done in two parts, as described in the experimental protocol.



Graph 1: soils sieving results

Mass percentage	SILT and CLAY(<75μm)	THIN SAND(75μm-0.2mm)	SAND(0.2mm-2mm)	GRAVEL(>2mm)
Red soil	~2.5	28.3	66	3.2
Mangalam soil	~4.7	29.8	55.8	9.7

Table 2: soils composition, by type of aggregates[6], obtained by sieving

Percentages are given with an accuracy of 0.1%, corresponding to the protocol described in part 3.2.1 p.16.

Conclusions:

- Regarding table 2, we can note a slight difference on distributions. The Mangalam soil has more gravels and more silt/clay than the red one, sandier. It is also shown on Graph 1: the sand in Mangalam soil is coarser than the one of the red soil. However, there is as thin sand (under 0.2mm) in the soil of Mangalam as in the red soil.
- Finally, according to graph 1 and table 2, we can conclude that the soil of Mangalam has a more regular gradation than the red one; latter is mostly composed of sands between 0.2 and 2mm (~66%). Referring to Dreux-Gorisse curves (7), we can here verify that regarding only the

[6] Silt and clay percentage is given from the last point corresponding to the thinner sieve (mesh = 0.075mm), bigger than the true limit [4] sand/silt (0.060mm).

gradation, the Mangalam soil has a better composition than the Red one for poured earth concrete. However, this conclusion does not take into consideration the type of clay, another really important parameter.

Limits:

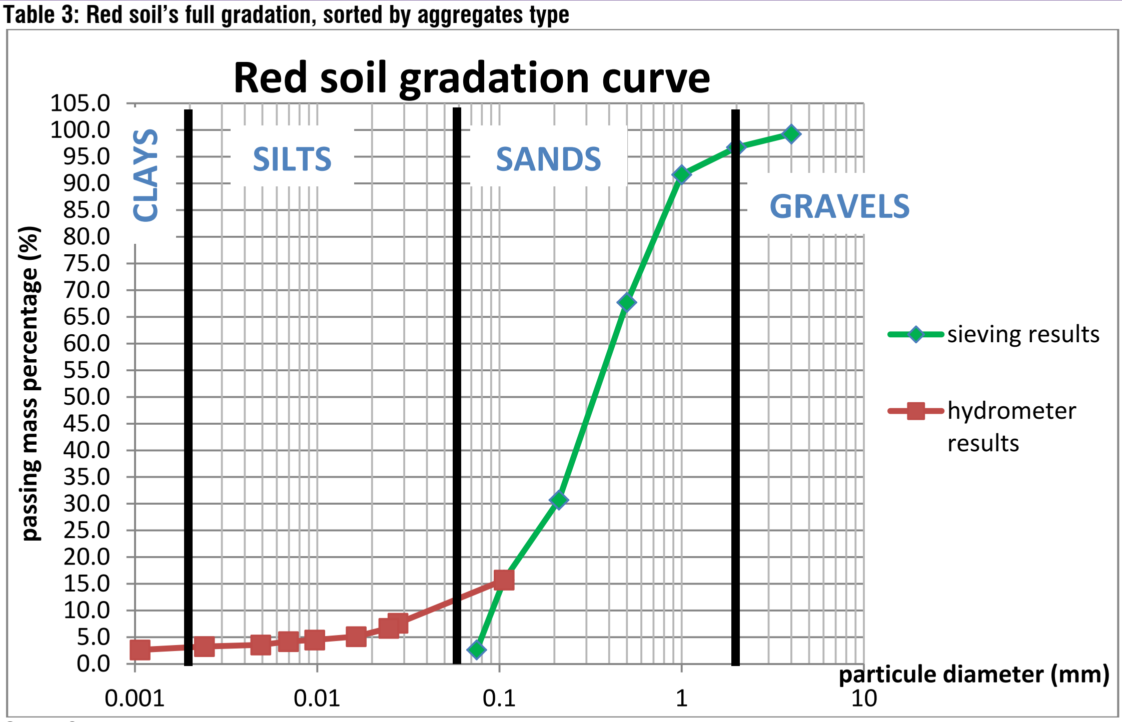
- Hand shacking is not as accurate as using a machine, more regular and faster, knowing that all sieves move at the same time.
- The oven used is difficult to use: the temperature oscillates between 90°C and 110°C when programmed at 100°C. Moreover, power cuts often happen, so we cannot be completely sure that samples were completely dry. That could induce aggregation of thin particles (clays and sands) and these aggregates would have been retained by bigger sieves that they should be.
- In order to compare results obtained with sensitive tests (which show at least 15% of clay, in volume, in the red soil) (5) it would have be interesting to know volumes percentage.
- The scale used (the one available), 2g accurate, was not really appropriate to do this measure accurately.

The next step for a more accurate graduation would be to use a more accurate scale (at least 0.01g), a sieving machine and to implement a wet sieving, washing aggregates with water while sieving. Another interesting study could be to measure the bulk density and the specific density of each fraction of soil passing different sieves.

Results obtained by sieving are then combined[7] with hydrometer tests results in order to have the full gradation curve of each soil.

	CLAY (<2.4µm)	SILT(2.4µm-27.7µm)	SAND(75µm-2mm)	GRAVEL(>2mm)
Mass percentage	3.2	4.4	94.2	3.2

Table 3: Red soil's full gradation, sorted by aggregates type

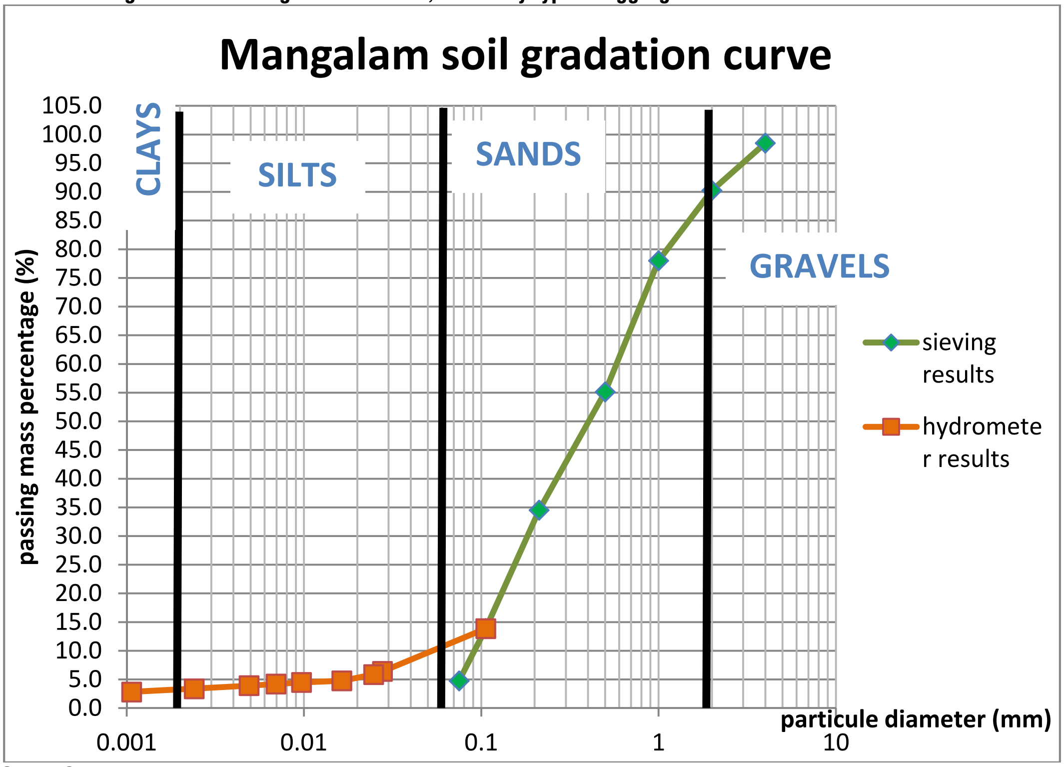


Graph 2: Red soil's full gradation curve

[7] In table 3 and 4, percentage of clay is given by the nearest point from the clay/silt; percentage of silt by the point corresponding to the biggest particles obtained with the hydrometer test; percentage of sand by the point corresponding to the thinner sieve. We decided to choose these points to more accuracy while "true points" are not directly given by the experimentation. "True limits" between different kinds of aggregates are in bold in graph 2 and 3 and are from (20).

	CLAY (<2.4µm)	SILT(2.4µm-28µm)	SAND(75µm-2mm)	GRAVEL(>2mm)
Mass percentage (%)	3.4	3	85.6	9.7

Table 4: Mangalam soil's full gradation curve, sorted by type of aggregates



Graph 3: Mangalam soil's full gradation curve

The error is difficult to estimate. Indeed, a first error could have been done on percentage passing 0.106mm mesh sieve. Others could have been done on hydrometer and time measurement (particularly for 3 first measures).

Conclusions:

- According to hydrometer's test results, there is more silt in the red soil than in the Mangalam one but as clay in the both. The quantity of clay and silt in both soils is really low (less than 8%).
- In graph 2 and 3, the first point corresponding to ~0.1mm diameter particles is the one obtained by sieving. Hydrometer measures give approximately twice clay+silt more than sieving results. That permits to show the difference of percentage obtained by sieving and by the hydrometer test for particles between 0.075mm and 0.1mm diameter. Indeed, hydrometer measures give approximately twice clay+silt percentage more than sieving results according to table 2, 3, and 4. We can suppose that the hydrometer test is not accurate but we can also suppose that the sieving, particularly for thinner particles, is not accurate enough and should be done longer and in wet conditions.

Limits:

- Percentage given for the hydrometer tests have to be carefully used: not any comparative test was done with a sample which the gradation curve is known.
- Moreover, knowing that determine the gradation of very thin particles really depends on the technique used (21)it would be better to compare the gradation with other techniques like laser diffraction. In another hand, the difference done here between clays and silts is only depending on particles size. It would be interesting to separate them chemically, with them composition, but also with them physical structure. A last point could be to determine the type of clay in the soil, in order to be able to predict better the clay behaviour, so the soil behaviour into the mix.

- Finally, if the solution is not really able to disintegrate well particles, some could have fall faster than they had if they were well separated. Finally, all approximations done (see part 3.2.2 p.17) could not be really true, distorting results.

Additional remarks are done in appendix 2 p.71 according to the visual sedimentation observed during one month.

According to all these remarks, these tests should be redone, with a university or private laboratory collaboration in order to determine really well the soil used, in order to be able to predict scientifically the behaviour of the soil adding water, reacting with additives used and drying.

4.2 USE OF "GRADATION TOOL"

Knowing densities of each aggregates used (see table 5), the gradation tool is used in order to model different mixes and then test and compare their specific densities.

Aggregates	Error (kg/L)	*RED SOIL*	*MANGALAM SOIL*	*1/2" GRAVEL*	*1" GRAVEL*	*2" GRAVEL*
ρ (kg/L)	0,07	*1,23*	*1,27*	*1,33*	*1,52*	*1,40*

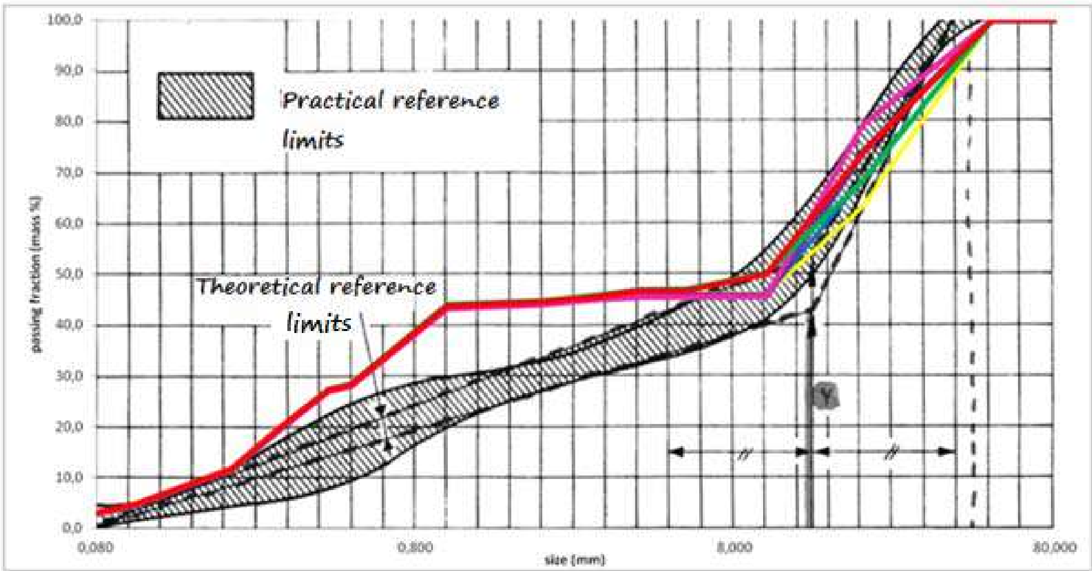
Table 5: recapitulative table for aggregates bulk densities

4.2.1 Soil modelling

Two amount of soil were tested: 40% and 50% of volume percentage. For each percentage of soil, different amount of different gravels and pebbles size were tested. The six best modelled densities (ones which approach the most the shaded curves according to the Dreux-Gorisse method, see graph 4 and 5) were kept for each amount of soil in order to do real experimentations.

Curve	Red soil (volume %)	½" (volume %)	1" (volume %)	2" (volume %)
	50	0	15	35
	50	0	20	30
	50	0	25	25
	50	0	30	20
	50	5	15	30
	50	5	20	25

Table 6: Volume percentage corresponding to graph 4



Graph 4: Modelled gradation curves, volume percentage given, 50% soil

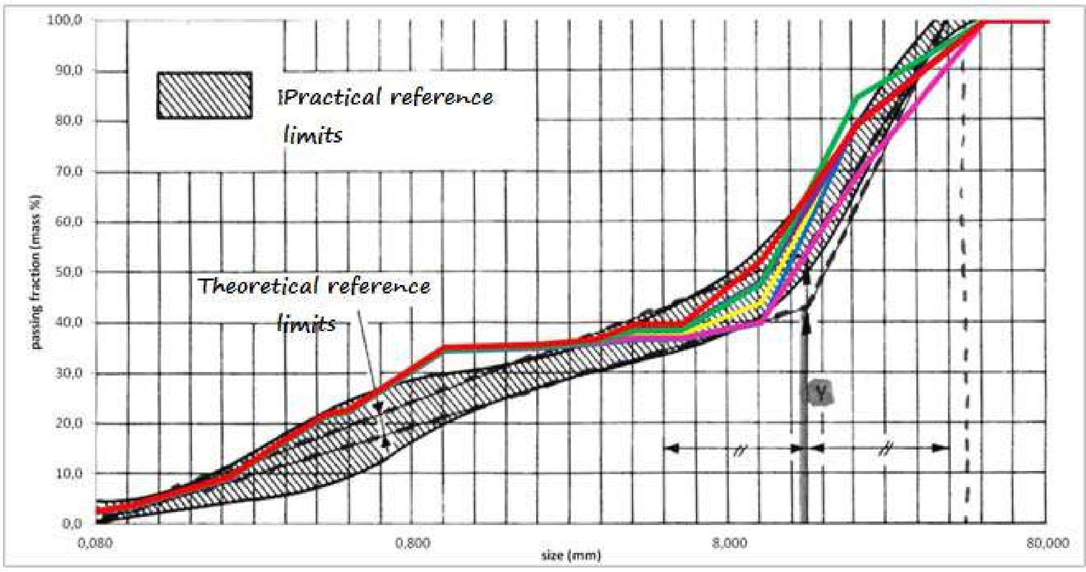
Modelling with 50% soil shows different things (graph 4):

- Gravels and pebbles with a size bigger than ½" must be added. Indeed, the sandy soil used brings too much fines aggregate to the mix compared with a usual concrete.
- In order to compensate the amount of thin aggregates in mixes with 50% of soil, the ½" gravels must be under 5% (percentage given in volume) and bigger gravels and pebbles are chosen.

- Because we chose to add a big percentage of soil, curves aspect can be changed only for the aggregates bigger than 3mm.

Curve	Red soil (volume %)	½" (volume %)	1" (volume %)	2" (volume %)
	40	10	30	20
	40	5	35	20
	40	15	25	20
	40	5	25	30
	40	15	30	15
	40	20	20	20

Table 7: Volume percentage corresponding to graph 5



Graph 5: Modelled gradation curves, volume percentage given, 40% soil

Modelling with 40% soil shows (graph 5):

- Gradation curves seem to be really better than for 50% of soil, particularly concerning aggregates between 1 to 8mm. Indeed, they fit better with the ideal area defined by Dreux and Gorisse.
- Curves are better spread in the shaded part for aggregates around 8mm than for 50% of soil. Indeed, the smaller amount of soil permits to try different ratios of ½" aggregates.
- The green curve is a little bit too high compared with the shaded part so we can assume that this mix will not give a good bulk density.

4.2.2 Soil mixes densities

According to modelling done above, different ratios of each aggregate were tested, measured by volumes and mass percentages were then calculated (refer to table 13 and table 14, in appendix 10, p.83). According to same tables, best mix for each percentage of soil was finally chosen to prepare samples. However, some densities are really close one from each other knowing the estimated error (0.035kg/L)[8] which could imply wrong choices.

Modelling for mixes with both soils was done and real specific densities were tested. However, knowing the error done, results for Mangalam soil mixes were very close to Red soil mixes specific densities. Thus, same gravels and pebbles proportions were chosen for mix with and without Mangalam soil. Indeed, even if gradations of these soils are quite different (28), densities are not modified enough to be accurately measured with the protocol set. Refer to table 11 in appendix 8, p.80 to know aggregates quantities.

[8] For all mixes, the sum of aggregates volumes added was 10L. Volume percentages used are rounded to 5%, implying the use of a 0.5L recipient to measure aggregates added. This is a little recipient compared with the size of biggest aggregates which imply big measurement errors.

4.3 SAMPLES CASTING, CURING AND DRYING

The casting of sample was the main source of error knowing that it was done by hand. Indeed, inhomogeneous samples can be expected and the use of biggest proportions of fibers or LAP was particularly difficult. In another hand, moulds were not rigid enough to keep perfectly set dimensions. However, this dimensions variations are counted in order to estimate the error done on different properties measurements.

Concerning the curing and drying, moving samples 2 days after being poured induce some damaged, particularly on cylinders edges. This surface variation will also be considered to calculate the compressive strength.

Additional remarks:

- It is possible that some surfaces are not perfectly parallels, because moulds were moving during the vibration step or because the smoothing was not well done. This fact can induce other forces during the compression test which indeed, will give an underestimated value.
- Some mixes were hardening really fast, which means that sometimes we had to add quite a lot of water to smooth the samples. This can also create a difference of behaviour between the smoothed surface and the rest.
- Moulds (cylinders and beams) were never removed after a constant time, knowing that some days three mixes were casting while some other days only one mix was casted.
- Beams moulds were not done in the same way from the beginning of the casting step to the end. Because of some shapes problems at the beginning, we had to improve it. So, this fact can induce some differences on beams' behaviour.
- The vibration machine had some problems. At one point, it was so bad that we had to restart the machine every five minutes. This means that some samples could have been better vibrated than others.
- Surfaces are flat, but holes corresponding to bubbles (around 1cm diameter and 0.5cm width), are visible in small quantities on the sides. Bigger holes due to a bad workability can be observed on sample with lot of coconut fibers.
- Important thin porosity (less than 0.5mm diameter) is also visible.

5. RESULTS AND DISCUSSIONS ON TESTS

This section will list all the results which had been obtained from the samples of each mix. Comparisons will be made between each mix and each solution (group of mixes), in order to consider all the results. This will help after to build the next steps for the poured Earth Concrete research.

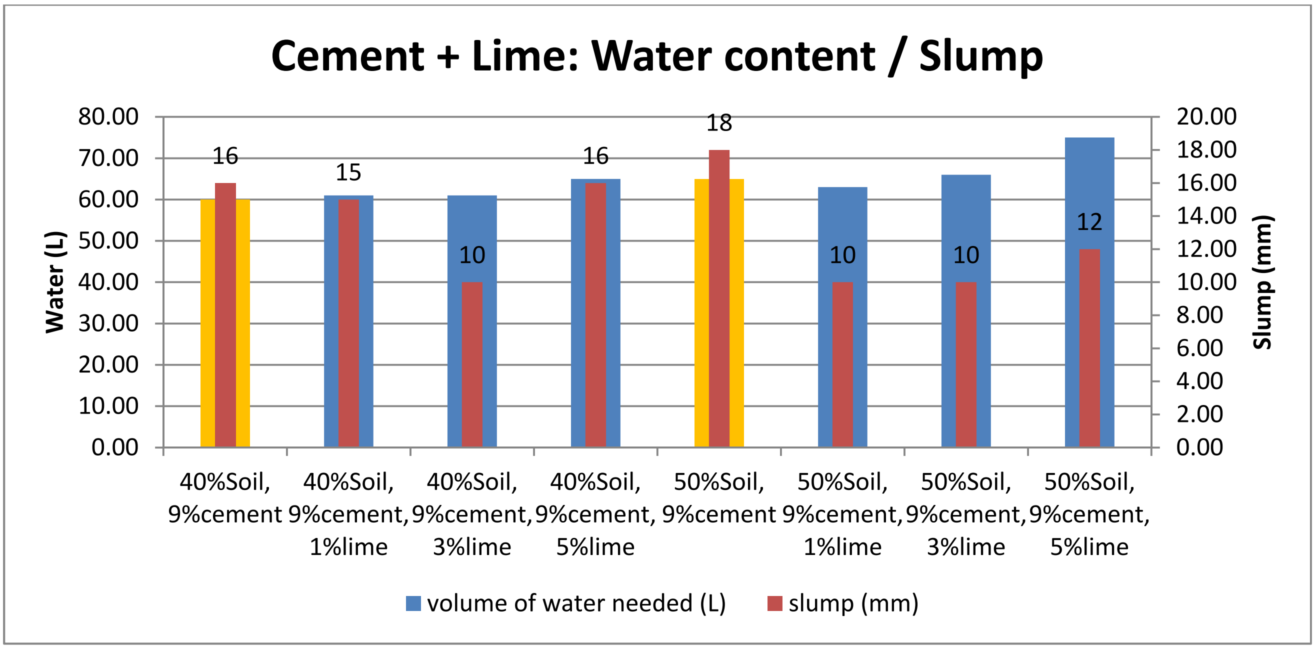
Each solution is presented one by one, giving the results about all the tested parameters. The order of this important:

- The first presented graph for each mix is about the needed water to obtain a good workability. This latter is determined by experience of the masons. Then, to verify, the slump test is done knowing that we want more than 10 mm slump.
- Then, we present the data which correspond to the casting period: the quantity of water added and the slump test results, for each and every mix. The water had been added until that we observe a good workability (mostly according to mason's experience).
- Then, we present the apparent density results because they are most of the time linked with all the other properties. While a classic concrete is about 2.4 kg/L, it's giving an idea by saying that the higher is the density the more we can reach good properties.
- So we will after present the water absorption and the shrinkage because, basically, if the Earth concrete is not dense, then it can be porous and so increase the water absorption. Given that water reacts with clay, it may create shrinkage.
- To finish the compressive strength, being the most important result, will be presented as a conclusion of all these properties.

5.1 CEMENT + LIME

The aim here was to study a complex reaction of stabilization. The adding of cement and lime bring us to a reaction between cement and lime as a unique stabilizer, and each of these components plus the mix of them will react with the clay. So, by changing the proportion of lime in this admixture, we change the proportion of each component in chemical reactions.
Knowing that we have as reference a mix without lime, we can after observe a point where cement and lime are effective.

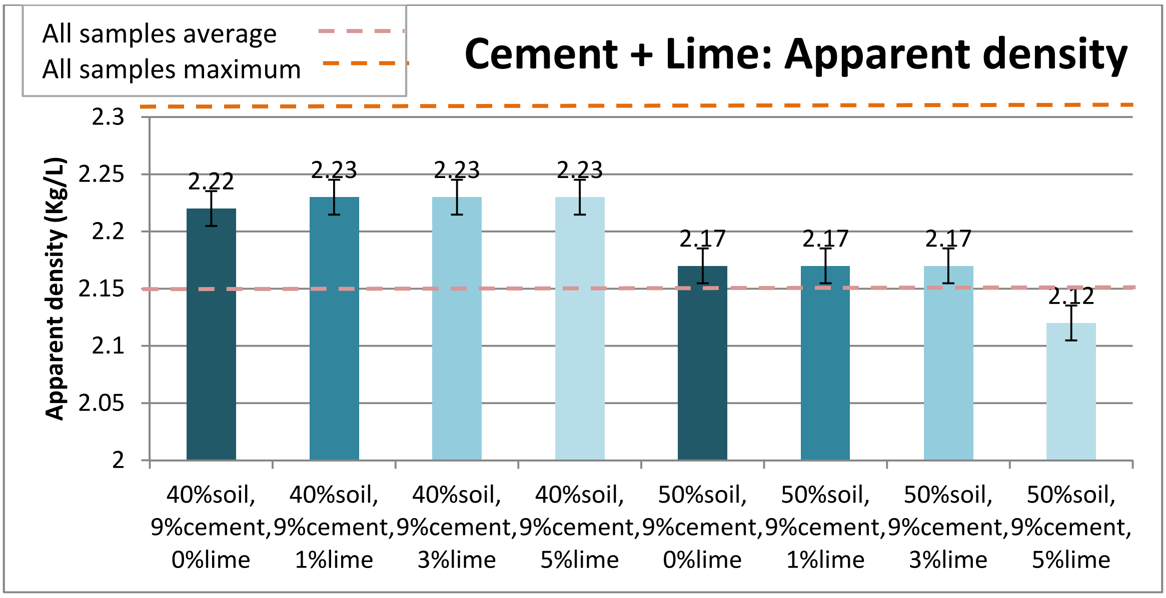
5.1.1 Water content and slump test



Graph 6: Water added during the casting of cement and lime mixes+ its corresponding slump test (slump tests error=1mm and water measures error=1L).

Our first observation is about the lime effect on workability. To reach a good one, it seems that the more lime is added, the more water we need. Secondly, more soil (40% to 50%) means also more water needed to reach a good workability. Concerning the slumps, it is hard here to find any interpretations.

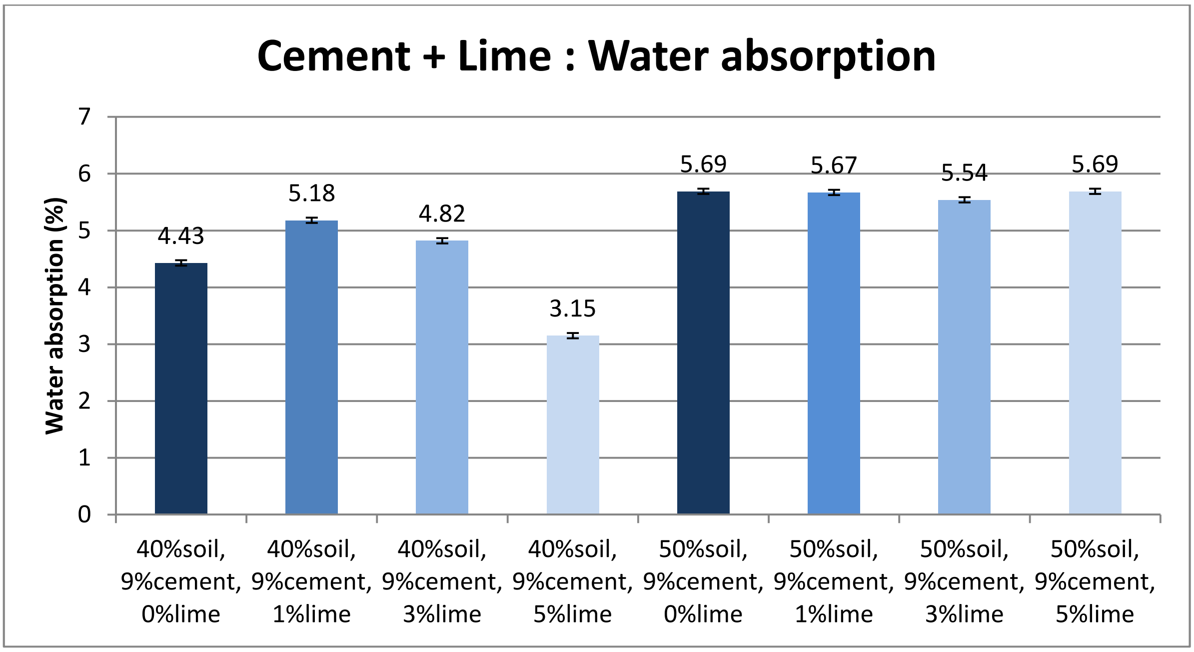
5.1.2 Densities



Graph 7: Apparent density of Cement + Lime samples (error=0.02%).

The first remarkable thing here is the difference between 40% and 50% of soil content. The density is significantly higher for only 40% soil, in these conditions (To see comparisons graphs, see appendix 12). Then, in the case of the 40% soil mixes, it seems that the percentage of lime does not affect the apparent density, while a high percentage of lime (5%) in the case of 50%soil decrease the apparent density. In terms of density itself, there are almost all above the average of all the studied samples. This means that we reach a good density here.

5.1.3 Water absorption

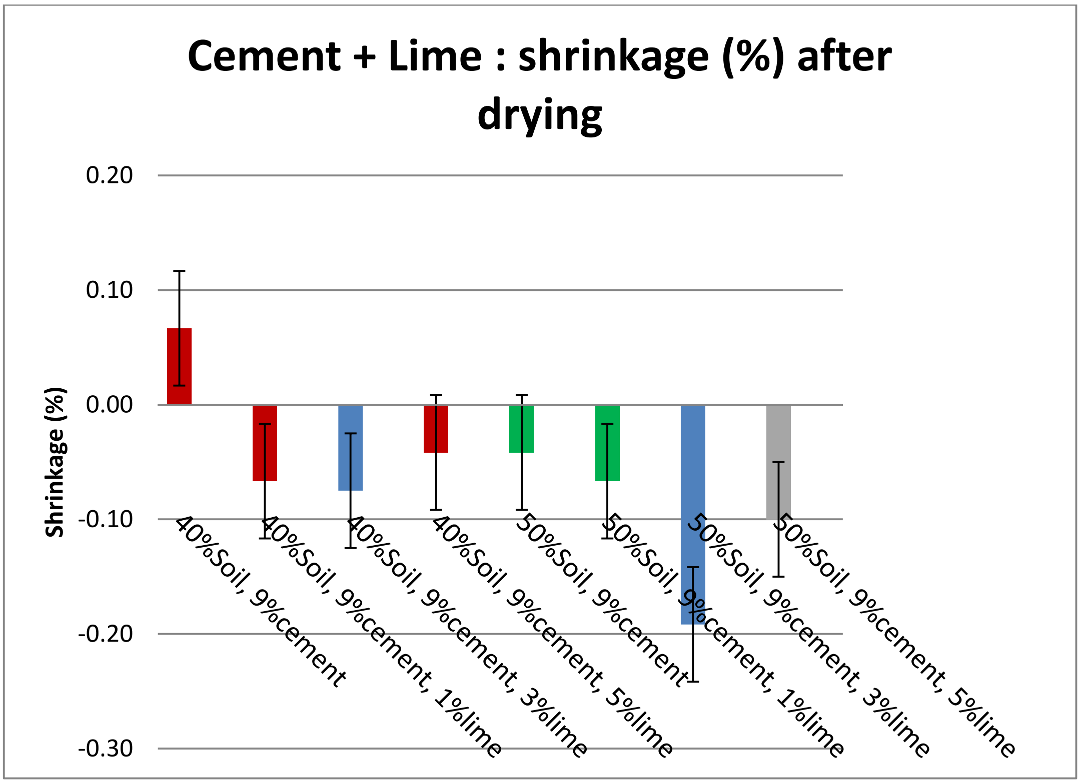


Graph 8: Water absorption capacity for Cement + Lime samples (error=0.05%).

In a same way, we notice that the 50% mixes absorb more water than the 40% soil. We will see in the "comparison" section if this event is general or not.

Nevertheless, while 50% soil mixes have approximately all the same water absorption (which can be explain by the fact that the soil content is at a high enough percentage to avoid other component's influence on water absorption), 40% soil mixes are affected by the lime percentage. The lime brings firstly an increase of the water absorption, but after the more lime percentage is high, lower is the water absorption.

5.1.4 Shrinkage



Graph 9: Shrinkage after the drying period (4 weeks of curing, then 1 week drying for samples without lime and 4 weeks for samples with lime) of Cement + Lime samples (error=0.05%).

Measurement errors, according to the ruler used and the line drawn, are really important (50% of the limit set for measures on beams) that could imply errors on conclusions

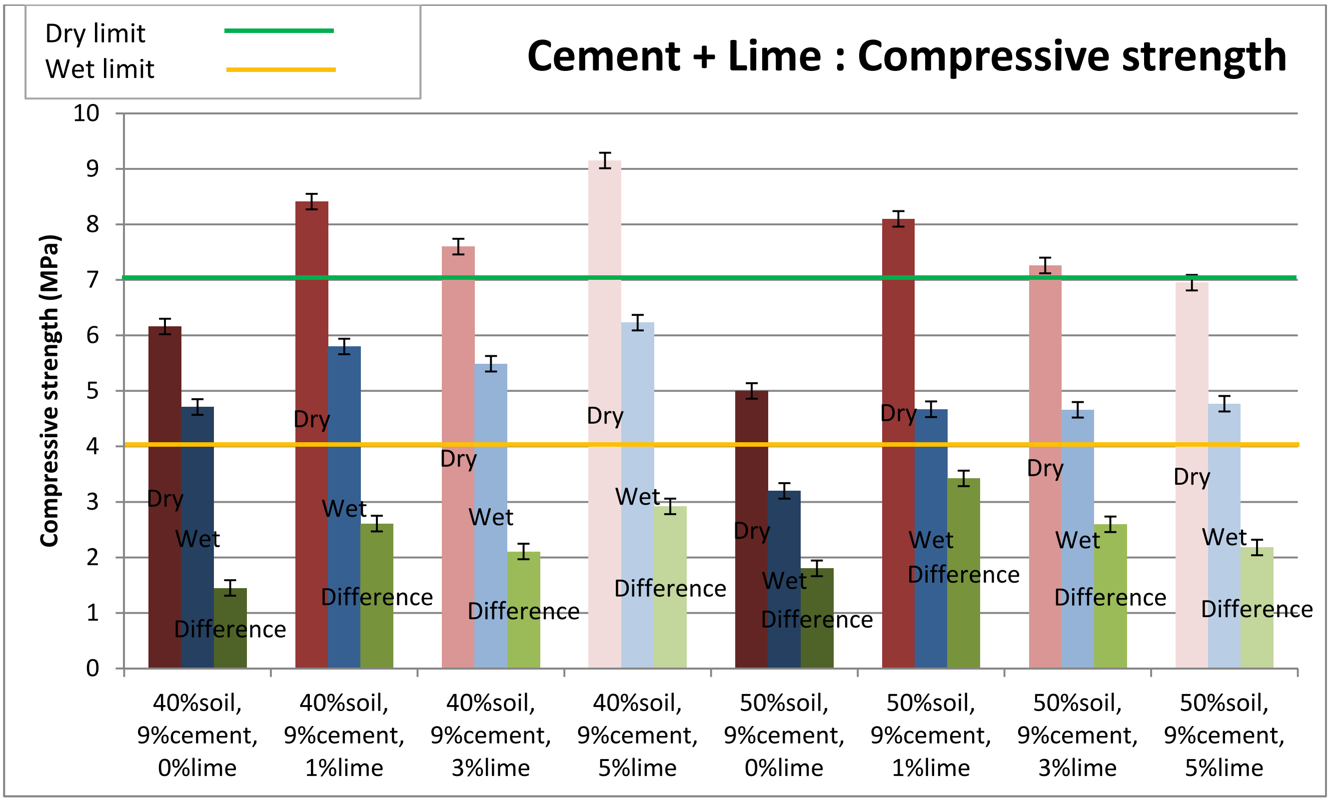
Only the mix *50%soil_9%cement_ 5%lime* is over the limit of 0.1% of shrinkage after the time of drying. The others seem to be relatively stable regarding the last figure of shrinkage.
But it is also interesting to see is how the sample moves all along the curing and drying period (see (29)).

Regarding the first positive result, which means they swell while curing, several explanations can be done on this curious fact:

- The beam's formwork was not well done, or removed too early (sometimes only 3hours after pouring), which induce a movement of the beam under its own weight while it is hardening.
- If the clay is still active (its reactivity is not killed by cement or lime chemical reactions), it can react with water (especially during the curing period). So it may induce swelling according to the presence of water on the Earth Concrete.

Finally, knowing that the mixing is done by hand, lot of water was added in order to increase the workability. Using a mixing machine should permit to reduce water quantities while ensuring a perfect homogeneity. This will also reduce mistakes done on shrinkage measurement.
(See the picture in the concluions part)

5.1.5 Compressive strength



Graph 10: Dry, wet and difference of compressive strengths of Cement + lime samples (error=0.1MPa).

Here are some really interesting results. We have here several mixes which go over the limits we had to reach. Mixing cement and lime seems to give some good results but we have to keep in mind that it is still a high percentage of stabilizers.

The influence of the lime content is here really interesting by the fact that it changes according to the soil percentage:

- For 40%soil mixes, 1% of lime is enough to reach limits of dry and wet compressive strength. Then, it decreases and increases again between 1% and 5%. Here it can be interesting to have more points in order to draw a curve and understand better the behaviour of the reaction. Because, knowing that the lime react with the clay (the lime's calcium cations replace the cations on the surface of the clay, and this reaction is promoted by the high pH environment of the lime-water system), it can mean that around 1% we are close from a good quantity where the chemical reactions are total. Then we also know that, when lime is added, more water is needed to have a workable mix, so that the 3%lime point can be a bridge between a good quantity for clay-lime chemical reaction and the fact that the more we have stabilizers, the stronger it will be.
- But this explanation does not work with 50%soil content mixes. Or the bridge might be longer so that we don't see the end. In a same way 1% is enough to reach the good properties (we must notice that the gap is really impressive = 3MPa of dry compressive strength difference) but after, the more we add lime the weaker is the earth concrete. Because it is logical that we need more stabilizer because of more soil, the point where the compressive strength goes higher again might be further.

Secondly, the wet compressive strength is, for 40%soil, moving as the dry one do. And we can notice that the difference between is also following the same movement. So it is possible that, for these conditions, the stronger is the earth concrete, the higher will be the difference between dry and wet compressive strength. This fact is almost also true with 50%soil content.

5.1.6 Conclusions

The following mixes have reached the wanted properties:

- ***40%soil_9%cement_1%lime***: This one is really interesting by the fact that each and every of its properties are good enough, and we don't use too much product, but it is still only 40%soil in the mix.
- ***40%soil_9%cement_3%lime***: Here we reach the wanted properties, but there is no interesting point because we add more stabilizers while the properties are worse than the previous mix.
- ***40%soil_9%cement_5%lime***: This mix is also really interesting because it shows that we can reach some high properties (9MPa of dry compressive strength). So if we want to use earth but in a zone where we need high properties, then it is possible to add enough stabilizers to do it.
- ***50%soil_9%cement_1%lime***: It is the most interesting here. On one side, we reach the wanted properties, all of them. On the other side, we observe a huge gap between the dry and wet compressive strength. Indeed, this mix has to be more studied: how the compressive strength is evolving through the time, why there is such a gap, how this earth concrete reacts with several periods of fully dried/water saturated…
- ***50%soil_9%cement_5%lime***: Like one the other before, this mix reaches the wanted properties but does not have really interesting points. The only fact is that we can explore further the lime proportions in order to see if there is a point where the compression strength rises again.

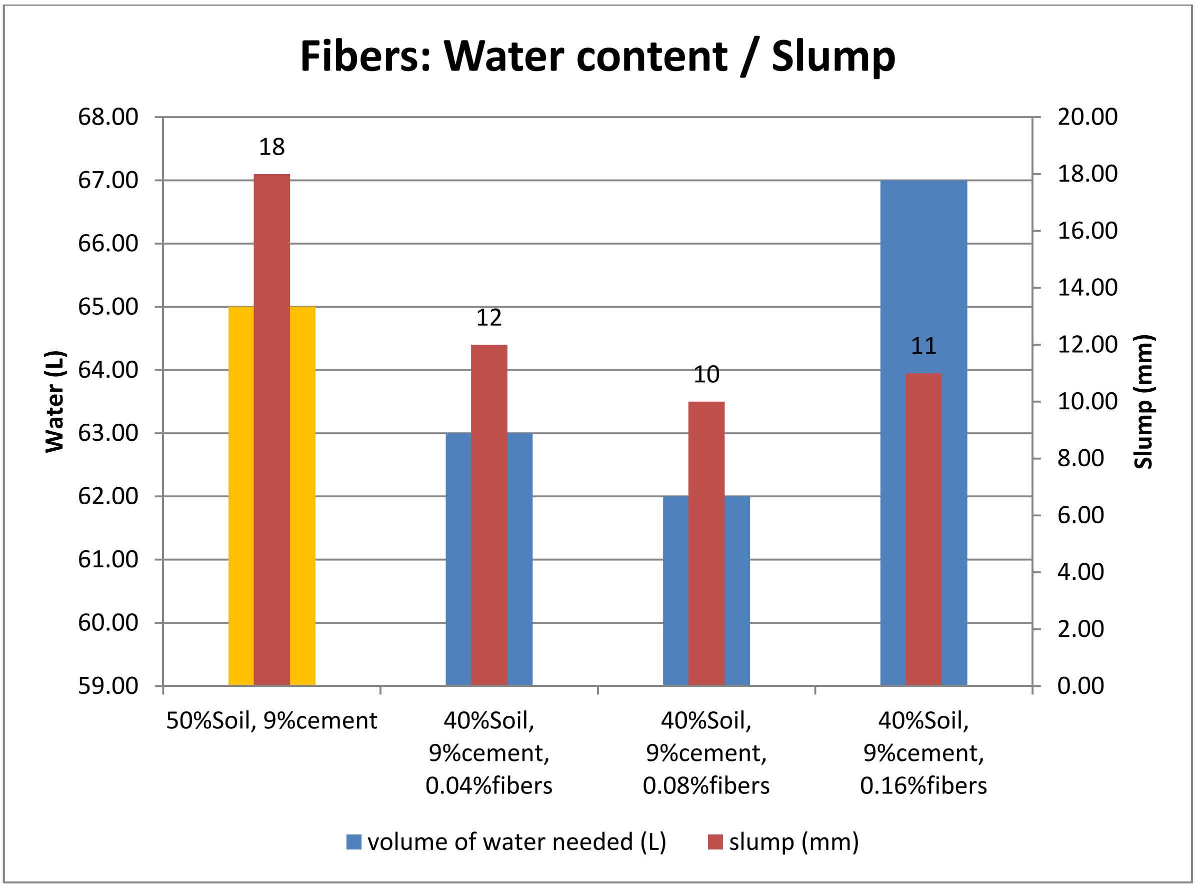
Picture 10: Example of *50%soil_9%cement_1%lime mix*

We can see here on the previous picture an example of the aspect of one of the mixes presented before. On this one we observe important cracks, even if the last shrinkage measure was not over the limit.

5.2 FIBERS

Coconut Fibers have been added to the Earth Concrete in a first wish to decrease the shrinkage. But actually, it can also improve the compressive strength and act like a kind of reinforcement.
This product is very interesting, even more here in India because it is a local material, cheap and huge quantities are available. In our case, only one fibers'length has been tested, or it is obvious that this length can affect the all behaviour. We also don't know how these fibers are gripped to the Earth Concrete, in our conditions, we observed a good grip but we actually don't know if there are any other possibilities.

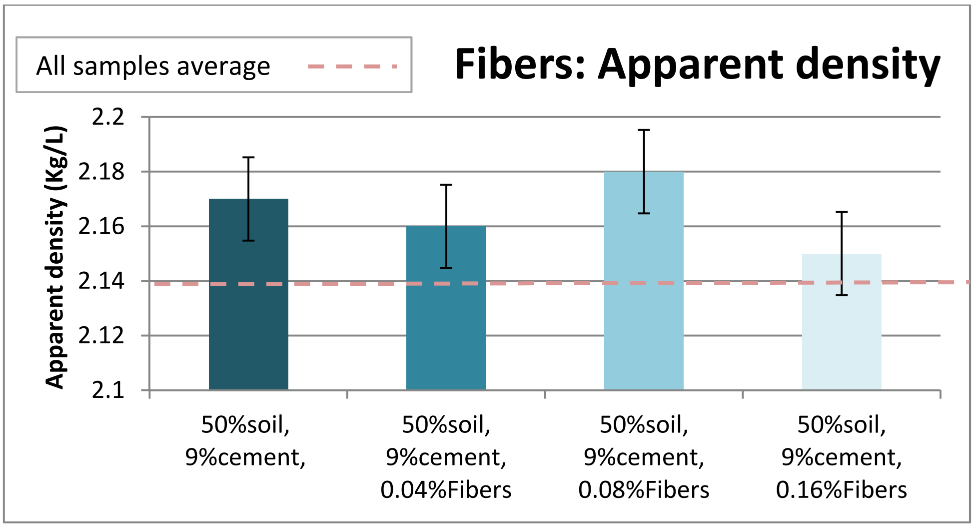
5.2.1 Water content and slump test



Graph 11: Water added during the casting of fibers mixes+ its corresponding slump test (slump tests error=1mm and water measures error=1L).

On the whole, fibers mixes had bad workability, because of the structure created by the fibers network. This may explain the fact that we used much more water for the mix with 8L of fibers. Concerning the slump tests, 1mm difference between them is not significant, so that we can consider that, in spite of the water content, we also have similar slump (so similar workability) between each of them.

5.2.2 Densities

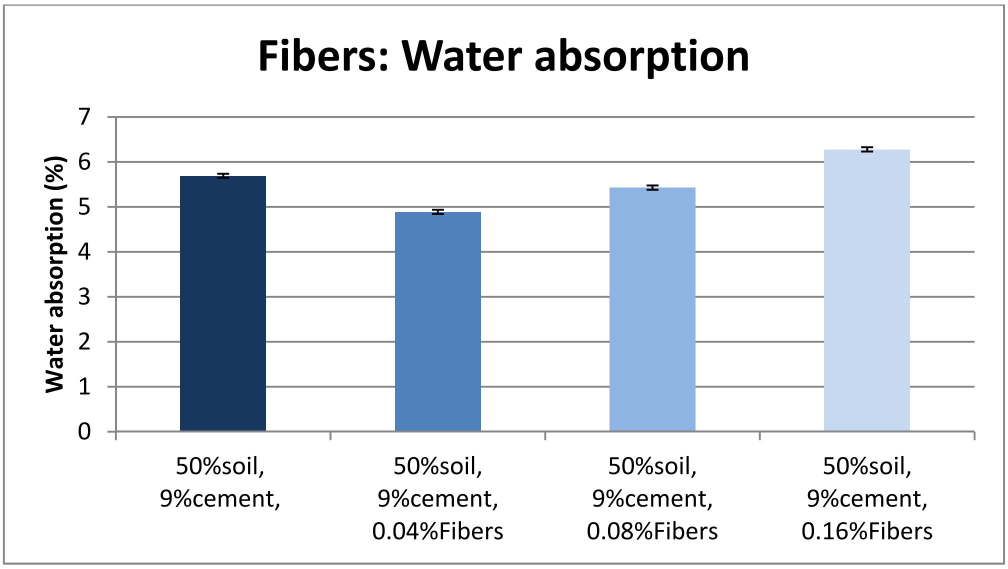


Graph 12: Apparent density of Fibers samples (error=0.02%).

(**Note**: The density for "*50%soil, 9%cement, 0,04%Fibers*" can be false, knowing that data were lost because of a power cut)

Adding fibers seems to decrease the density (around 0.02 kg/L increasing the amount of fibers around 0.08 percents) disregarding the "*50%soil, 9%cement, 0,04%fibers*" measure, not accurate. Indeed, fibers have a very low density that could decrease the final density of the sample.

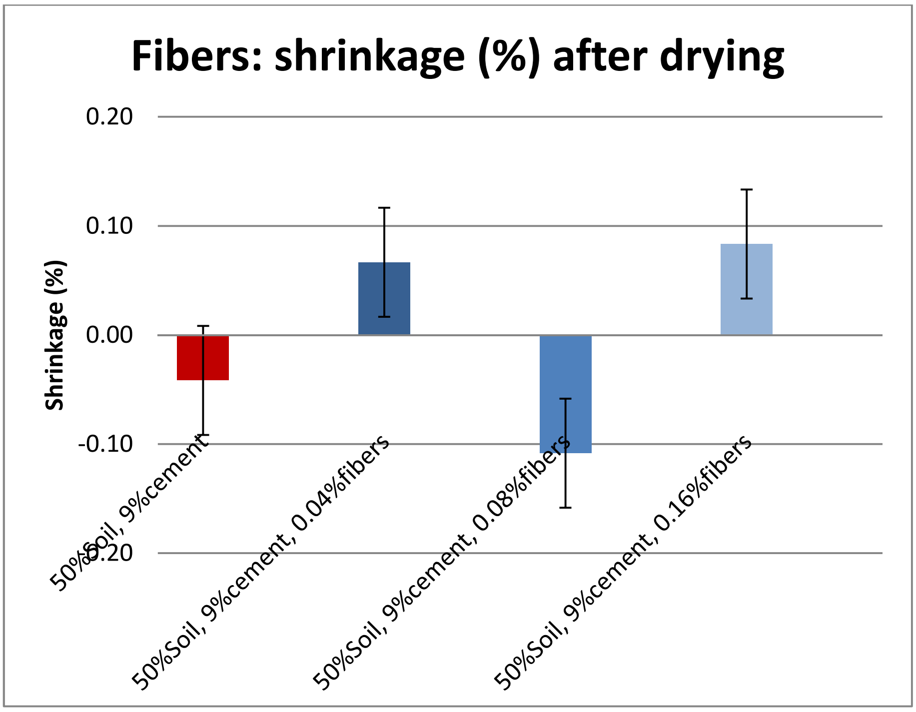
5.2.3 Water absorption



Graph 13: Water absorption capacity for Fibers samples (error=0.05%).

Addition of fibers increases the water absorption. Indeed, fibers may be a kind of canals to bring water into the sample as they are organic materials. And, as we saw before, the density of these three fibers mixes are lower than the reference (same mix without fibers) which can also have an influence on the water absorption.

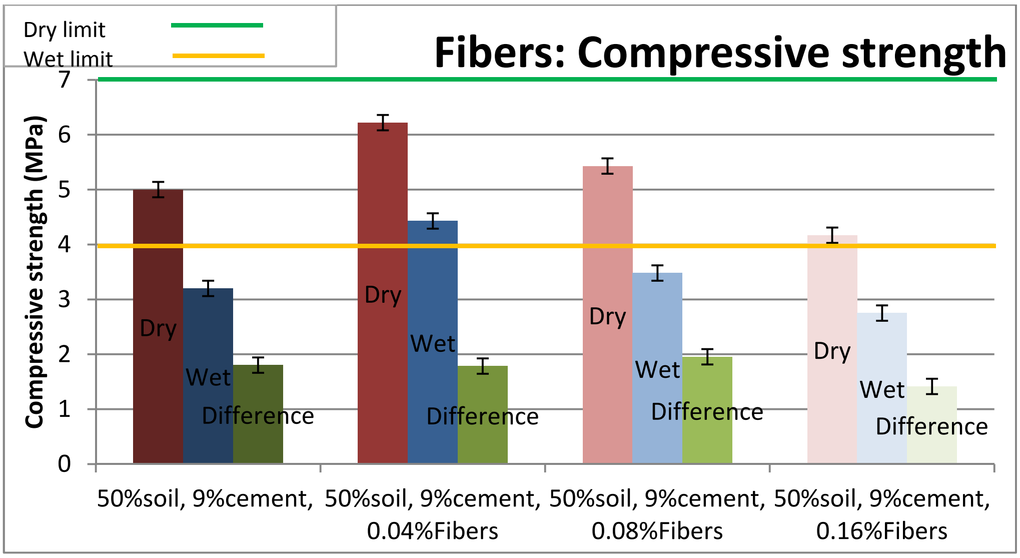
5.2.4 Shrinkage



Graph 14: Shrinkage after the drying period (4 weeks of curing, then 1 week drying for samples without lime and 4 weeks for samples with lime) of Fibers samples (error=0.05%).

Addition of fibers seems to not have the effect wanted. However, knowing that the shrinkage for the control sample (*50%soil, 9%cement*) was better than the set limit, measures accuracy could not be enough to show the variation while adding fibers.

5.2.5 Compressive strength



Graph 15: Dry, wet and difference of compressive strengths of Fibers samples (error=0.1MPa).

Addition of a little amount of fibers (0.04%) increase the compressive strength (around 1MPa dried and wetted) but a higher amount (0.08% and 0.16%) makes it decrease (~1MPa dried and ~0.5MPa wetted). On another hand, we increase the dry compressive strength, but we actually also increase the wet one (even if the fibers can create more water absorption). Moreover, the difference between dry and wet compressive strength stays relatively the same between the two firsts fibers mixes.

5.2.6 Conclusions

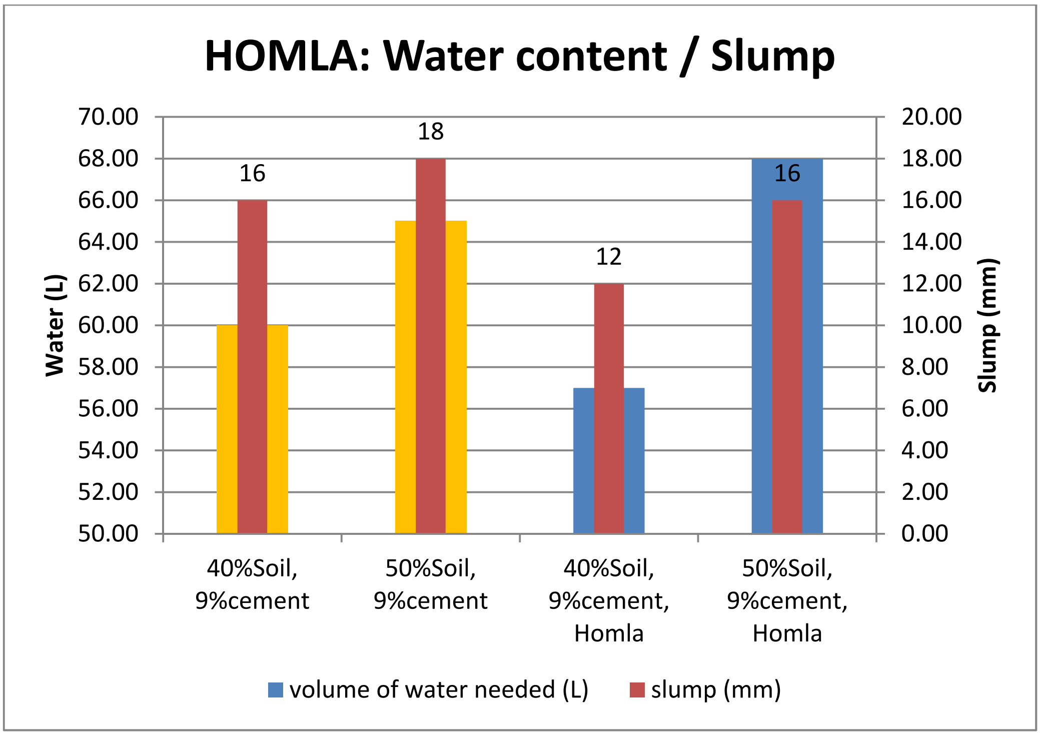
Coconut fibers have actually really interesting points to be developed. We did not get super results, they don't reach wanted properties, but we are close to them and we observed that coconut fibers are effective and can really improve the compressive strength by improving the tensile strength.
For this reason, fibers in general should be studied again, going deeper in the different possibilities:

- Because just one length has been studied, different mixes should be done with different lengths of fibers.
- We did it with coconut fibers, but other kind of fibers could be studied. For example, horse dung is full of fibers, with an interesting gradation (different sizes).

5.3 HOMLA

HOMLA (for Homeopathic Mix of Lime and Alum) was mainly tested for its production of ammonia, which should be a waterproof agent for the mix. It could be an interesting product, knowing that we use a natural stone by only crushing and mixing it with lime. Moreover, the lime-alum solution is easy and quick to prepare, but you need protection (glasses and masks) against the ammonia gaz.

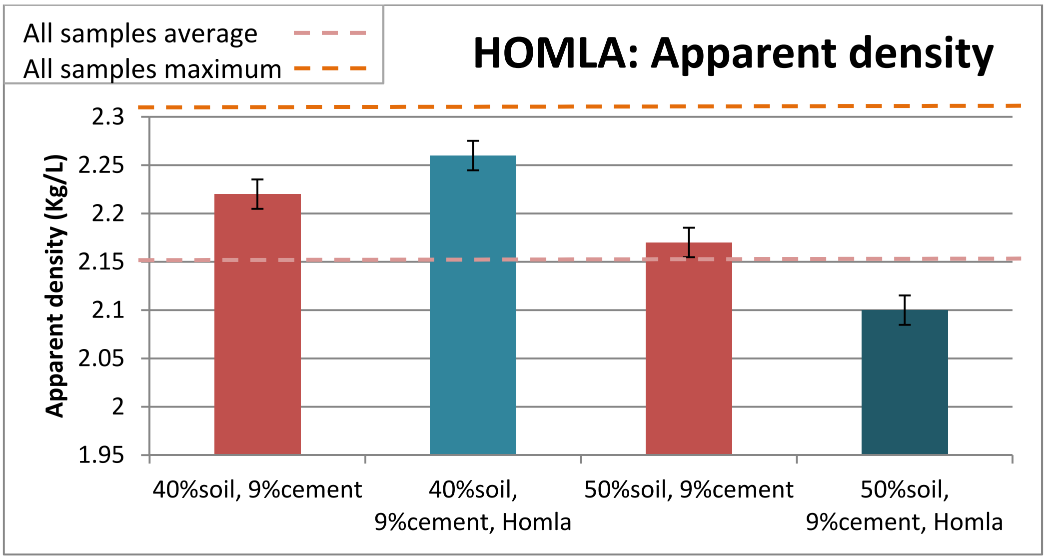
5.3.1 Water content and slump test



Graph 16: Water added during the casting of HOMLA mixes+ its corresponding slump test (slump tests error=1mm and water measures error=1L).

A difference of 11L is observed between the water content of the 40%soil mix and the 50%soil (HOMLA mxes). As usual, more soil need more water. We cannot know if this difference is also influenced by the fact that we use HOMLA water. This difference has to be put into perspective, because there is also a difference of slump.

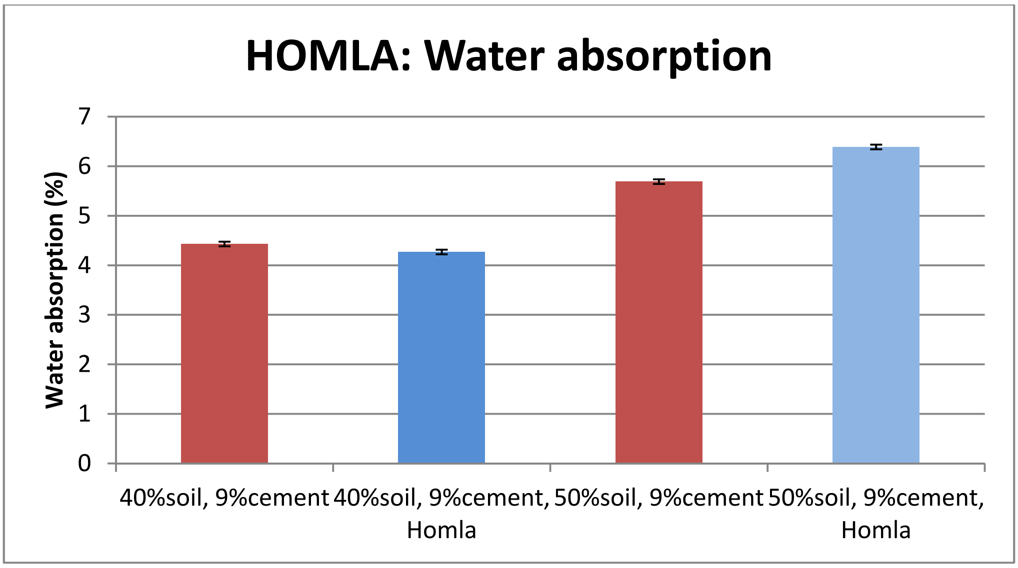
5.3.2 Densities



Graph 17: Apparent density of HOMLA samples (error=0.02%).

Some curious points are given here for the HOMLA results. The apparent density is increased by the lime-alum solution for the 40%soil case, while it makes it decrease for the 50%soil case.
A first explanation can be the water content which is higher for 50%soil. This means that we could have done a better mix with less water. However, it is hard to explain that the HOMLA solution can improve the density of the mix. Because it was not an expected effect, we don't really know how the ammonia, or dissolved minerals in the solution, can have an effect on the density of the mix. It can be a simple mistake, but here is a point to be explored.

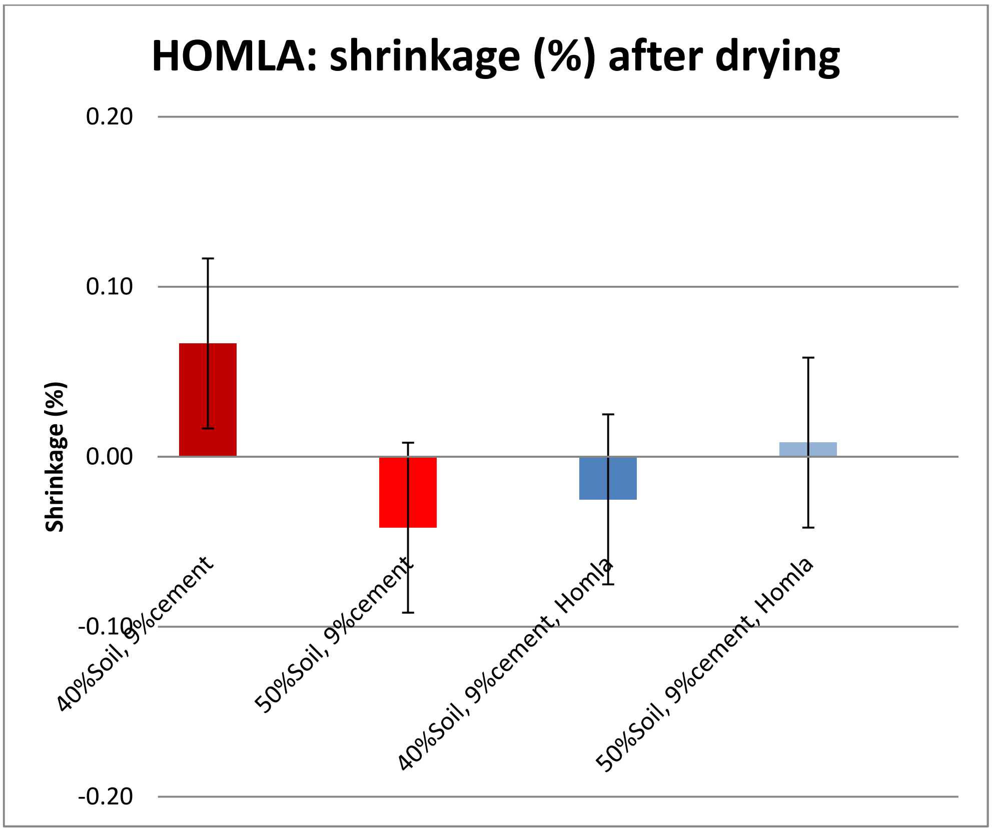
5.3.3 Water absorption



Graph 18: Water absorption capacity for HOMLA samples (error=0.05%).

By the link between density and water absorption, here is the exact opposite of the density results. The more the mix is dense, the less it can absorb water. So that means that we cannot really observe the effect of the HOMLA solution as a working waterproof agent. Moreover, even if the 50%soil HOMLA mix has a lower density, it still absorbs much more water than the mix without HOMLA.

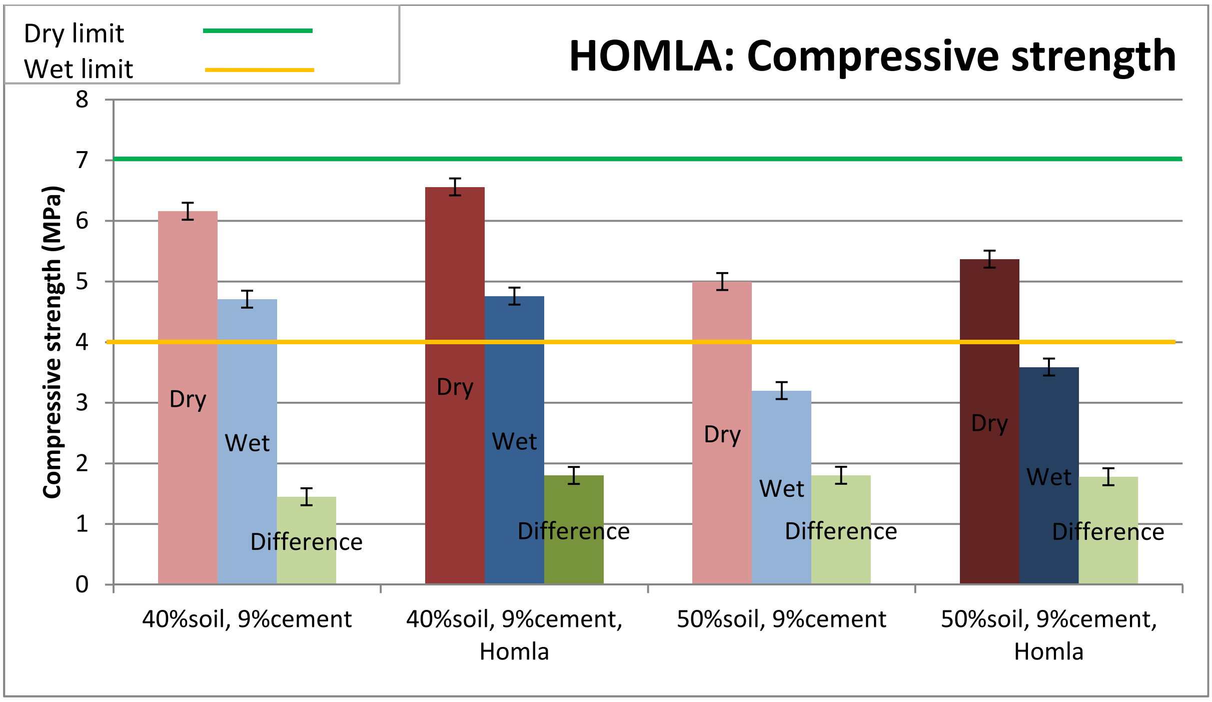
5.3.4 Shrinkage



Graph 19: Shrinkage after the drying period (4 weeks of curing, then 1 week drying for samples without lime and 4 weeks for samples with lime) of HOMLA (error=0.05%).

Even if errors are still too big to give any right interpretations, we still notice behaviour's differences between classic mixes and HOMLA mixes. It seems that shrinkages are always lower with the HOMLA solution. So, maybe, we can say here that the waterproof agent acts as a stabilizer in the way that it prevents any Earth Concrete's movements by avoiding moisture influences.

5.3.5 Compressive strength



Graph 20: Dry, wet and difference of compressive strengths of HOMLA samples (error=0.1MPa).

None of the HOMLA mixes reach the wanted dry compressive strength, but for the 40%soil content mix the wet compressive strength limit is reached.

As for the density and the water absorption, the 40%soil content HOMLA mix is better than his classic brother, in terms of compressive strength. Nevertheless, regarding the previous results (density and water absorption were worse than the classic mix), it was not expected that the compressive strength of the 50%soil content HOMLA mix could be better than the mix without the lime-alum solution. The question here is how the mix can be stronger while it is less dense and can absorb more water? As we said in the previous section, it may be possible that the HOMLA act as a stabilizer. But this time, it affects also the inside structure of the mix by making it stronger.

5.3.6 Conclusions

The results are clear in terms of waterproofing power. It can be interesting to know how exactly works the ammonia, what are its chemical reactions with the different components of the Earth Concrete, and how can it acts as a waterproofing agent. It is possible that we just don't have enough data to see its effect.

On another hand, there are some interesting results which can be detailed:

- HOMLA solution seems to have an effect on the density
- HOMLA seems to prevent shrinkage
- HOMLA can, according to our result, make the Earth Concrete stronger

These three facts should be studied, by first going deeper in the chemical reactions of this solution in order to find how can observe them in a better way.

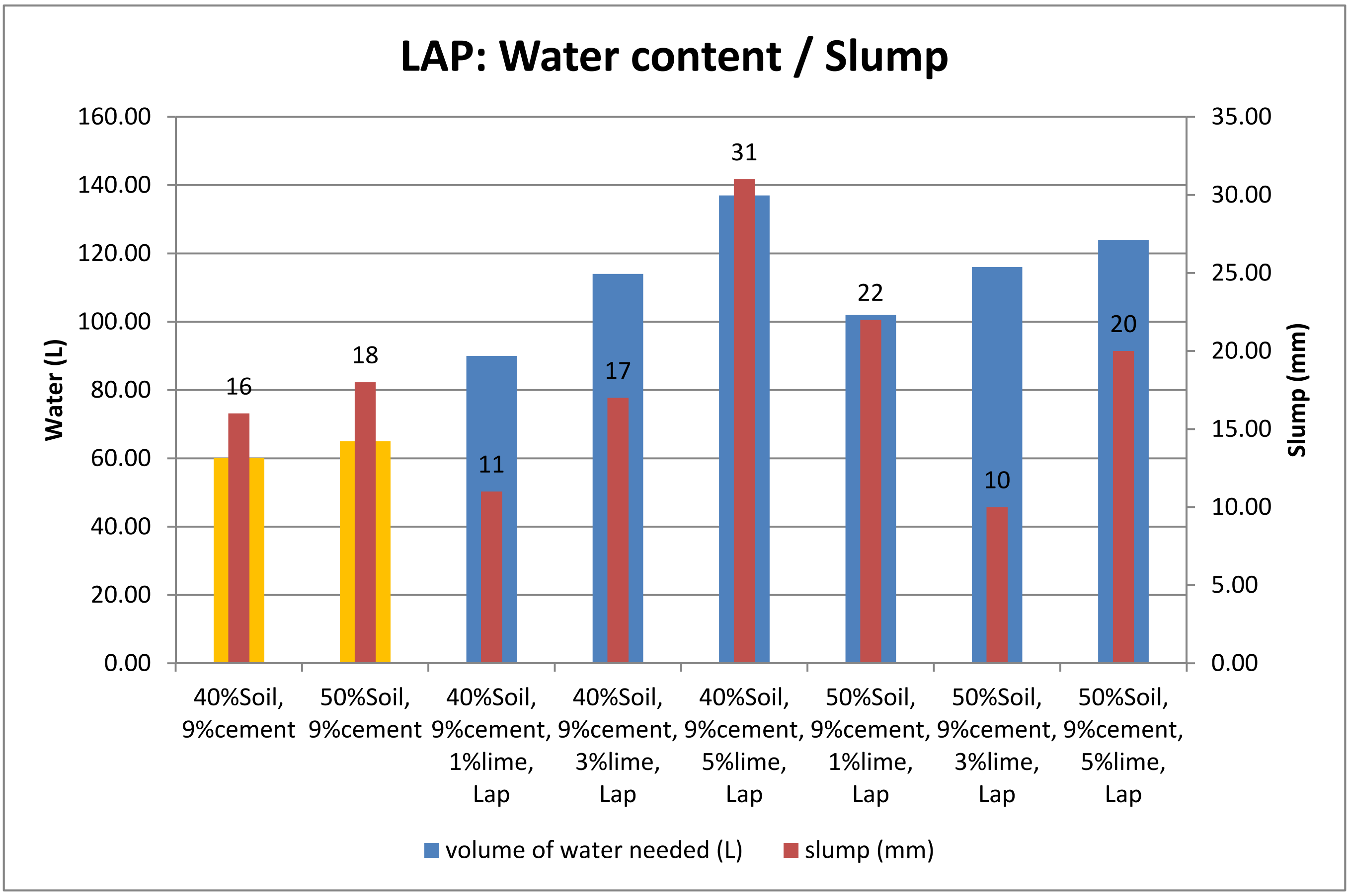
5.4 LAP

As it was the case for HOMLA, LAP (for Lime-Alum paste) has for aim to prevent water absorption by the production of a waterproofing agent, the ammonia. But, the difference is that here we also add a lime percentage which will be used as a stabilizer.

It is possible that we were wrong with the proportions of lime-alum and water while we were preparing the paste. Because this one was too solid, so mixing it with the dry mix was quite hard, which explain why we have lumps of reacted lime. Nevertheless, the mix was effective in terms of ammonia production, we had to wear glasses and masks.

Picture 11: LAP mixing, adding Lime Alum Paste

5.4.1 Water content and slump test

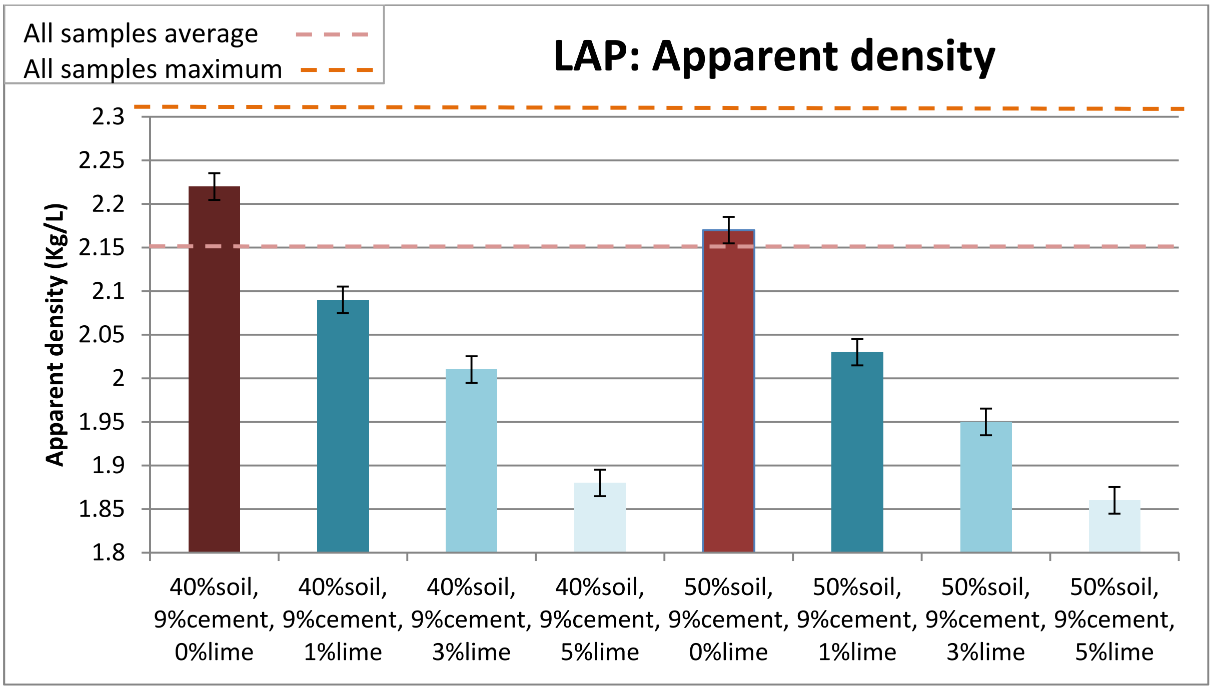


Graph 21: Water added during the casting of LAP + its corresponding slump test (slump tests error=1mm and water measures error=1L).

Here, the water needed is increasing with the amount of lime. This is quite logical because, firstly, when the paste is prepared, the more we need to add lime, the more alum-water is needed. But then, given that when the amount of lime is increasing, the amount of paste also, which means that it is also harder to mix, so need more water.

Then, slump tests are not always following the water content simply because it was not well mixed.

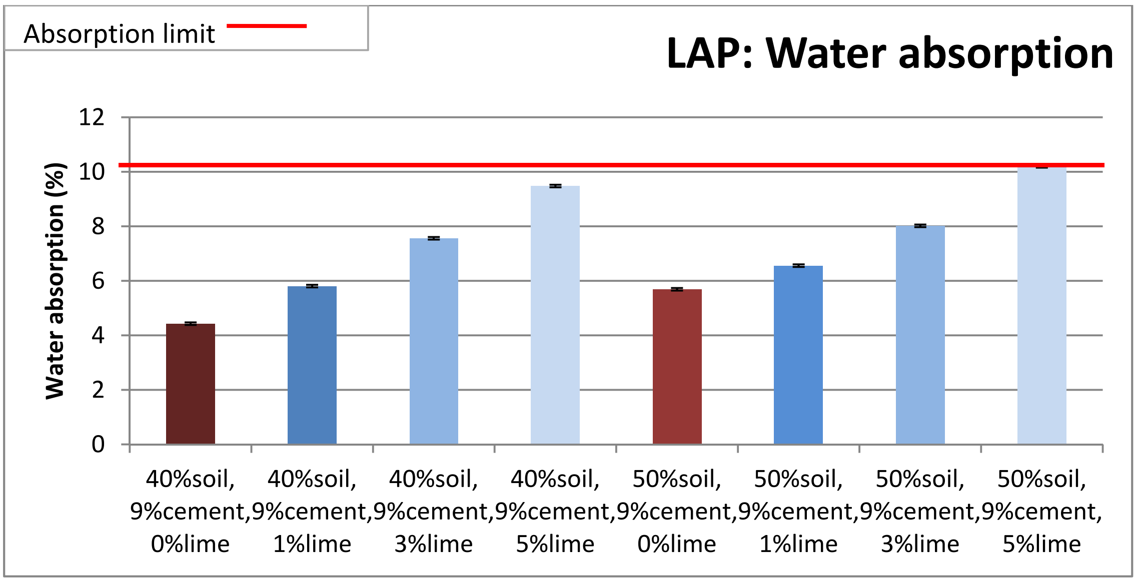
5.4.2 Densities



Graph 22: Apparent density of LAP samples (error=0.02%).

We can see that, for LAP mixes, everything is really linked. Here, as the percentage of lime is increasing, the apparent density is decreasing, which is mostly because of the increasing of the number of lumps (reacted lime is very light, so the number of lumps decrease easily the density of the whole mix). Finally, all the LAP mixes are under the average. This fact is significant of the bad quality of the mix.

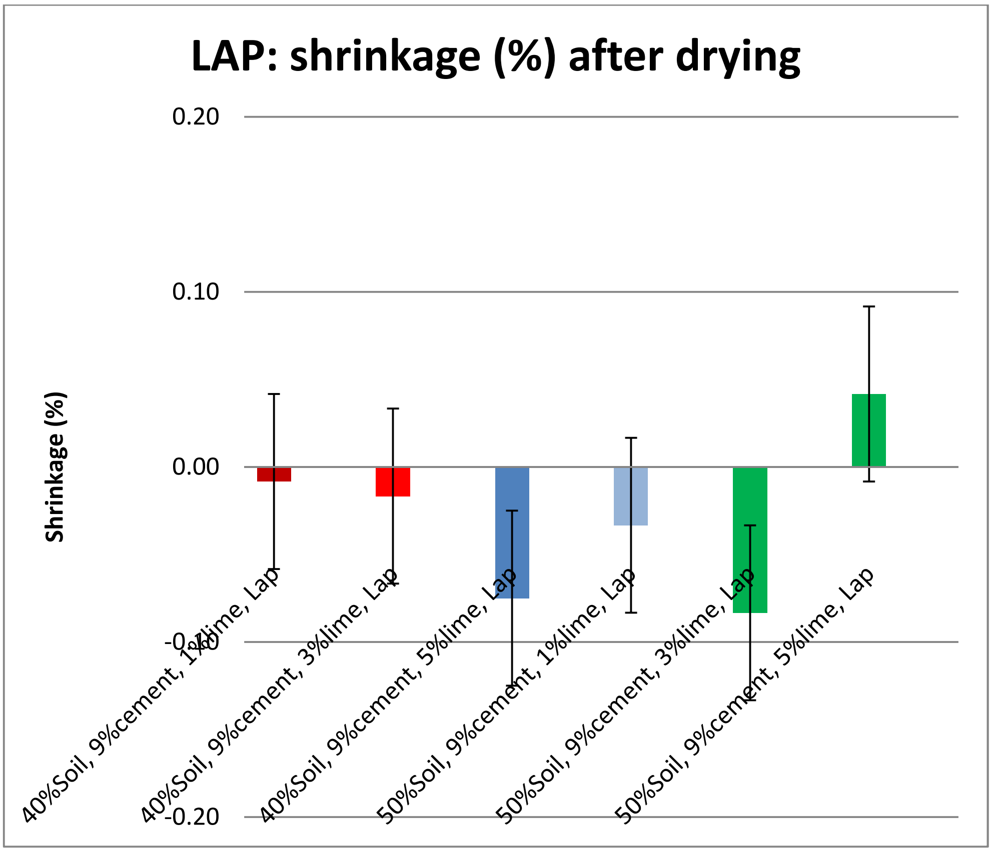
5.4.3 Water absorption



Graph 23: Water absorption capacity for LAP samples (error=0.05%).

While the apparent density increases with the augmentation of lime amount, the water absorption decreases. Because of the bad quality of these Earth Concrete mixes, the water finds easily a way to go inside the samples. Even if most of them does not go over the limit, they reach a quite high point of water absorption, and their differences between them is, for what we can see, only related with the lime percentage. Because of that, we cannot observe any waterproofing power neither verify the ammonia effect on any of them.

5.4.4 Shrinkage



Graph 24: Shrinkage after the drying period (4 weeks of curing, then 1 week drying for samples without lime and 4 weeks for samples with lime) of LAP samples (error=0.05%).

Apparently, Lap mixes have low shrinkages. Most of them are negative and under the limit of 0.1% of the total length, while one of them (50%, 9%cement, 5%lime, Lap) is positive. This fact has several explanations. Some of them were presented before (see part 5.1.4 p35), but we can here also mention the fact that lime has specific reactions with clay (chemical reactions, has it was explained before). This can explain this positive measure: too much lime could produce a high capacity for the Earth Concrete to shrink.

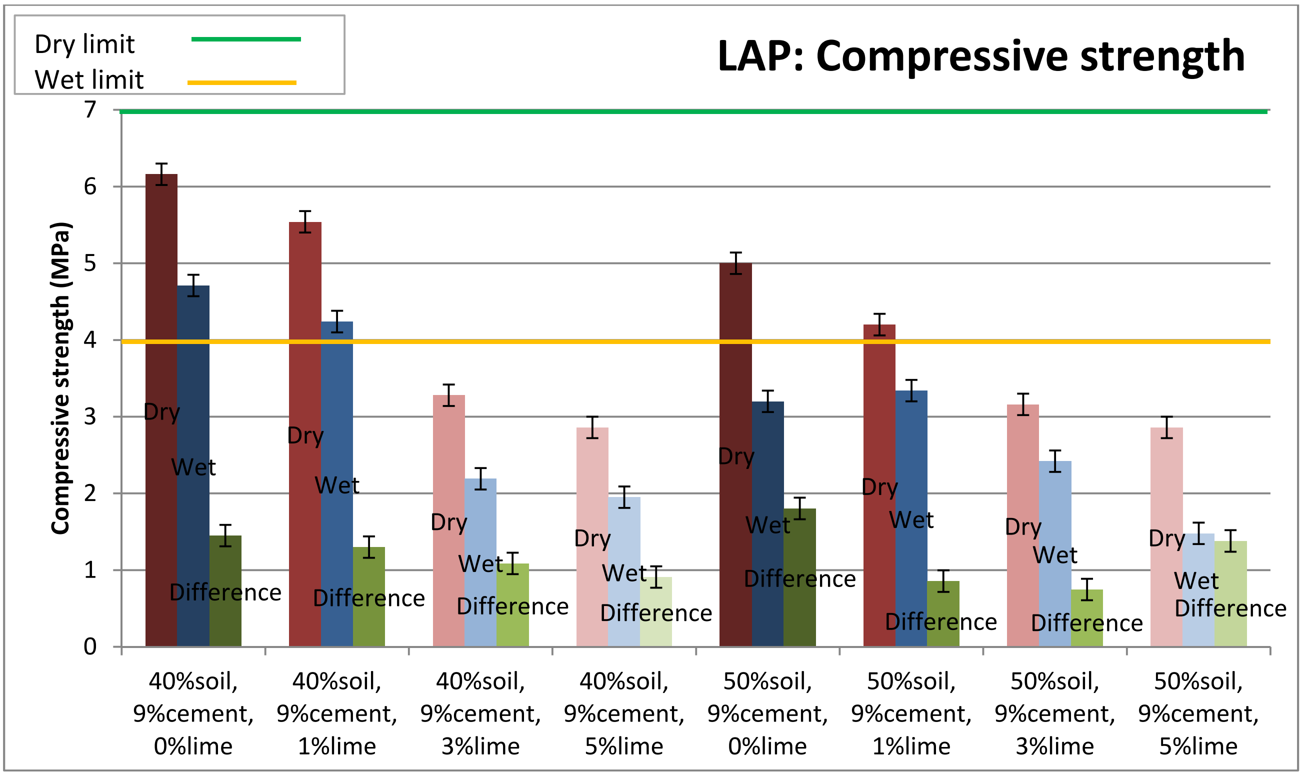
The previous results (densities and water absorption capacities) show bad properties, while here the shrinkage does not go over the limit.

Picture 12: 50%, 9%cement, 5%lime, Lap Beams

Picture 13: 50%, 9%cement, 1%lime, Lap beams

We can observe on the previous pictures (11 and 12), that the shrinkage value does not really represent the fact that we can observe cracks. Some beams will shrink or swell without cracking, while other will do.

5.4.5 Compressive strength



Graph 25: Dry, wet and difference of compressive strengths of LAP samples (error=0.1MPa).

According to all the previous items, the final compressive strength is also very low. Everything is also decreasing following the augmentation of lime percentage. Because of these facts, we cannot keep anything very interesting on these results.

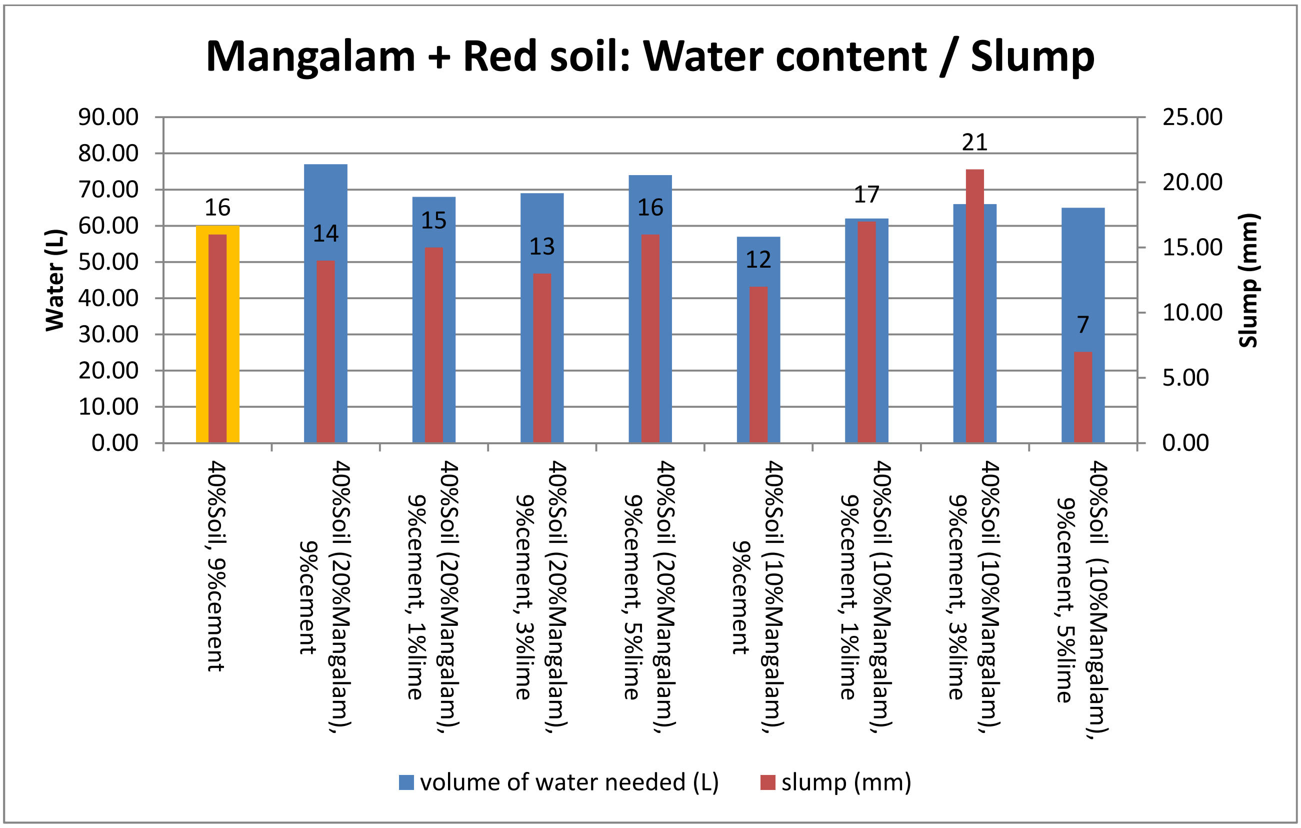
5.4.6 Conclusions

Despite the fact that we had only bad results for all LAP mixes, it could be interesting to try again, making sure that the quantities of lime-alum-water can make a liquid enough paste which can be easily mixed with the dry mix.
On another hand, as for the HOMLA mixes, you need protections like glasses and masks to be able to work with these additives. Knowing that we are searching for natural additives, it also means that we are supposed to work with healthy component, which is not the case here.
It could be also good to make researches on natural sources of waterproofing agent which are less dangerous, or a source of ammonia which does not need protections.

5.5 MANGALAM SOIL + RED SOIL

Here is one of the most important series of mix. Given that the project of the Mangalam School was in progress, and that Poured Earth Concrete was supposed to be used, we were trying to find how we can use the soil from there to apply our technic. Knowing from some previous research on CSEB that this soil has a totally different behaviour, we did not know what can be expected from these mixes of two soils.
Because of this point, the fact that we were trying without and with different percentages of lime give interesting results (as we said before, lime has a different reaction than concrete with the different components of soils).

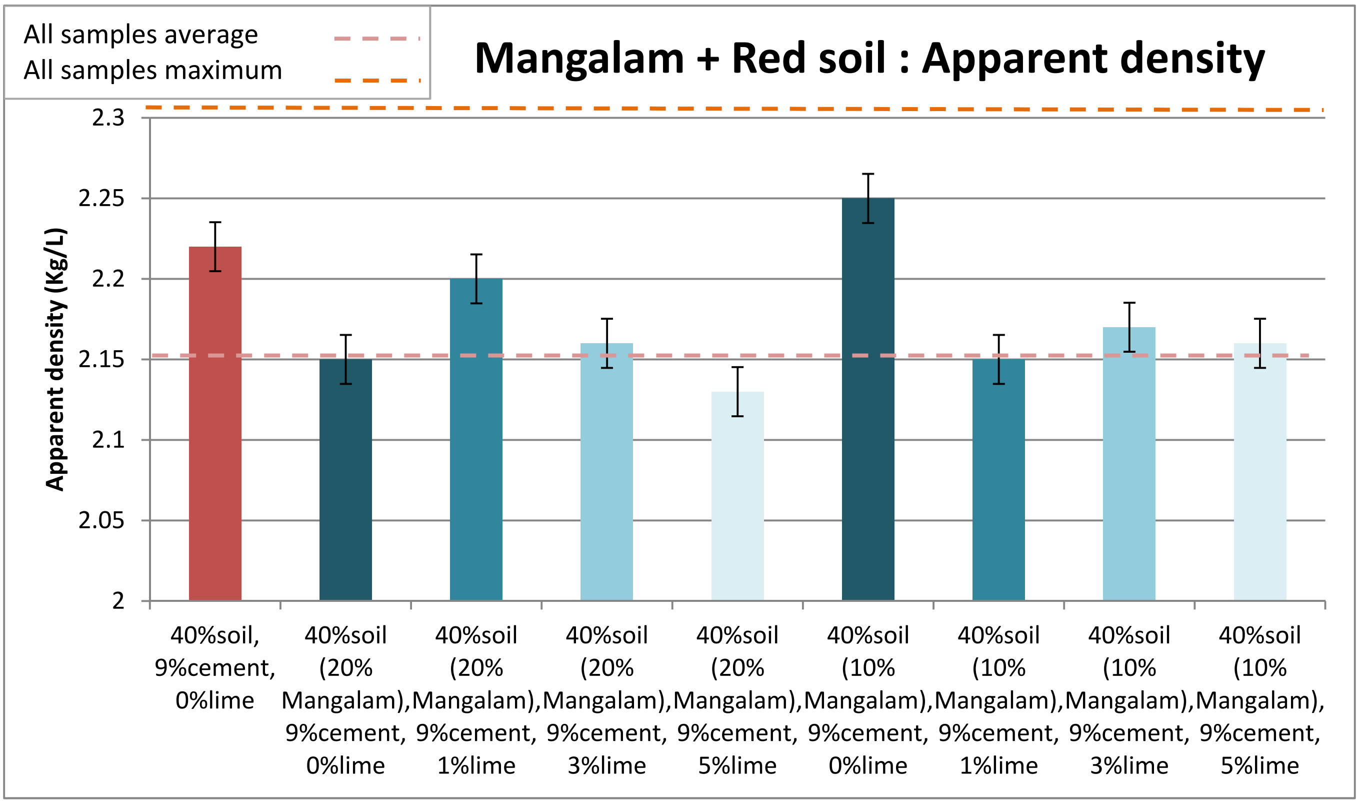
5.5.1 Water content and slump test



Graph 26: Water added during the casting of Mangalam and Red soil mixes+ its corresponding slump test (slump tests error=1mm and water measures error=1L).

As it has been observed before, the quantity of lime influence the workability and so the water needed to get a good one. But, by comparison with the classic Earth Concrete (*40%soil, 9%cement*), the addition of mangalam soil has also some influence on the workability. Given that the amount of water is poured until that we just "see" that is enough, we can't really say that 10% of mangalam soil (*40%soil (10% Mangalam), 9%cement, 0%lime*) decreases the quantity of needed water. However, 20% of mangalam soil (*40%soil (20% Mangalam), 9%cement, 0%lime*) is obviously giving the mix a worse workability so that it needs more water. The question is: it is because of a different gradation, or because of different clay's behaviour?

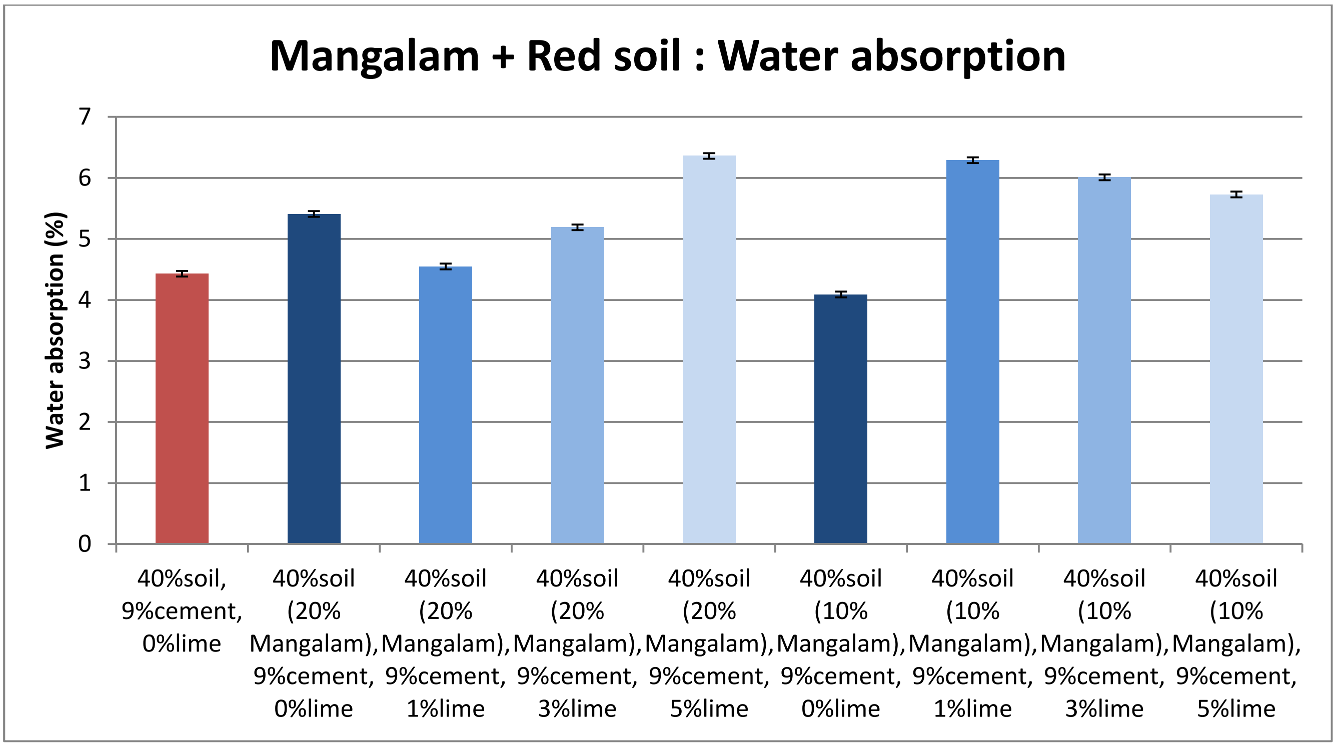
5.5.2 Densities



Graph 27: Apparent density of Mangalam and Red soil samples (error=0.02%).

The apparent density shows here multiple things. First, mangalam soil has an observable effect on the density. As we see, too much mangalam soil (20%) is decreasing density while a lower percentage (10%) is increasing the density. Indeed, it must be interesting to go deeper in this way in order to know where the higher point of density according to the mangalam soil percentage is. Secondly, we almost observe the same fact for the addition of lime. For the 20%mangalam soil mixes, it is the case (a little percentage, around 1%, of lime increase a lot the density). But it is not the case for the 10%mangalam soil mixes, where lime makes decrease the density.

5.5.3 Water absorption



Graph 28: Water absorption capacity for Mangalam and Red soil samples (error=0.05%).

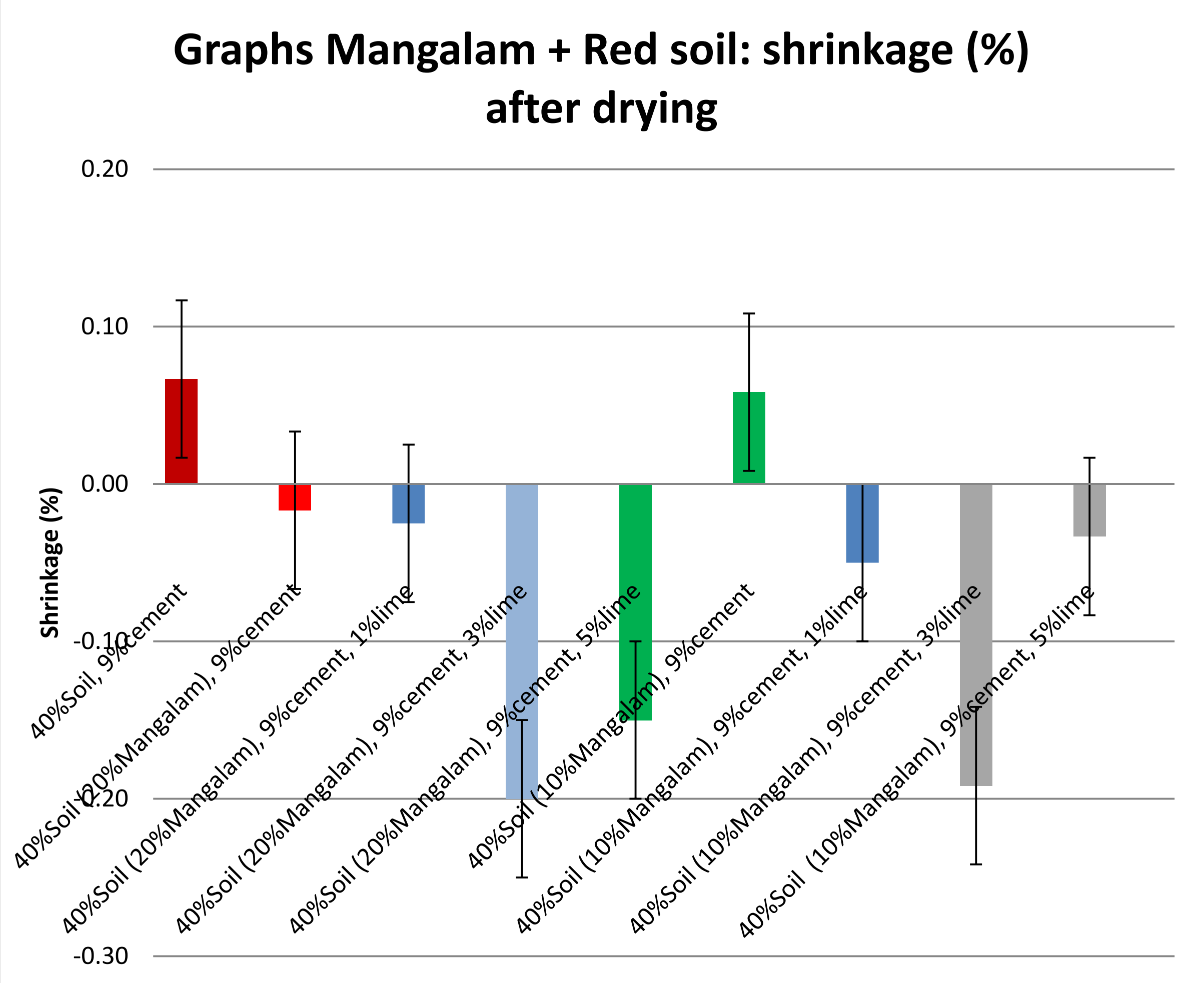
The first remark here is that we observe the almost exact behaviour than for the apparent density, which means that they are directly linked and there is no other intervening parameter on this fact.

The only contradiction point is about the *40%soil_(10% Mangalam)_9%cement_5%lime*, its density decrease while its water absorption also.

Picture 14: Example of a crushed saturated sample

The previous picture shows that, in most of the case, the water cannot penetrate until the sample's centre. Knowing that this fact depends on the mix composition, we have an application of the concept of water absorption. On another hand, this fact can induce mistakes for the wet compressive strength test, all the samples are not really in the same "state".

5.5.4 Shrinkage



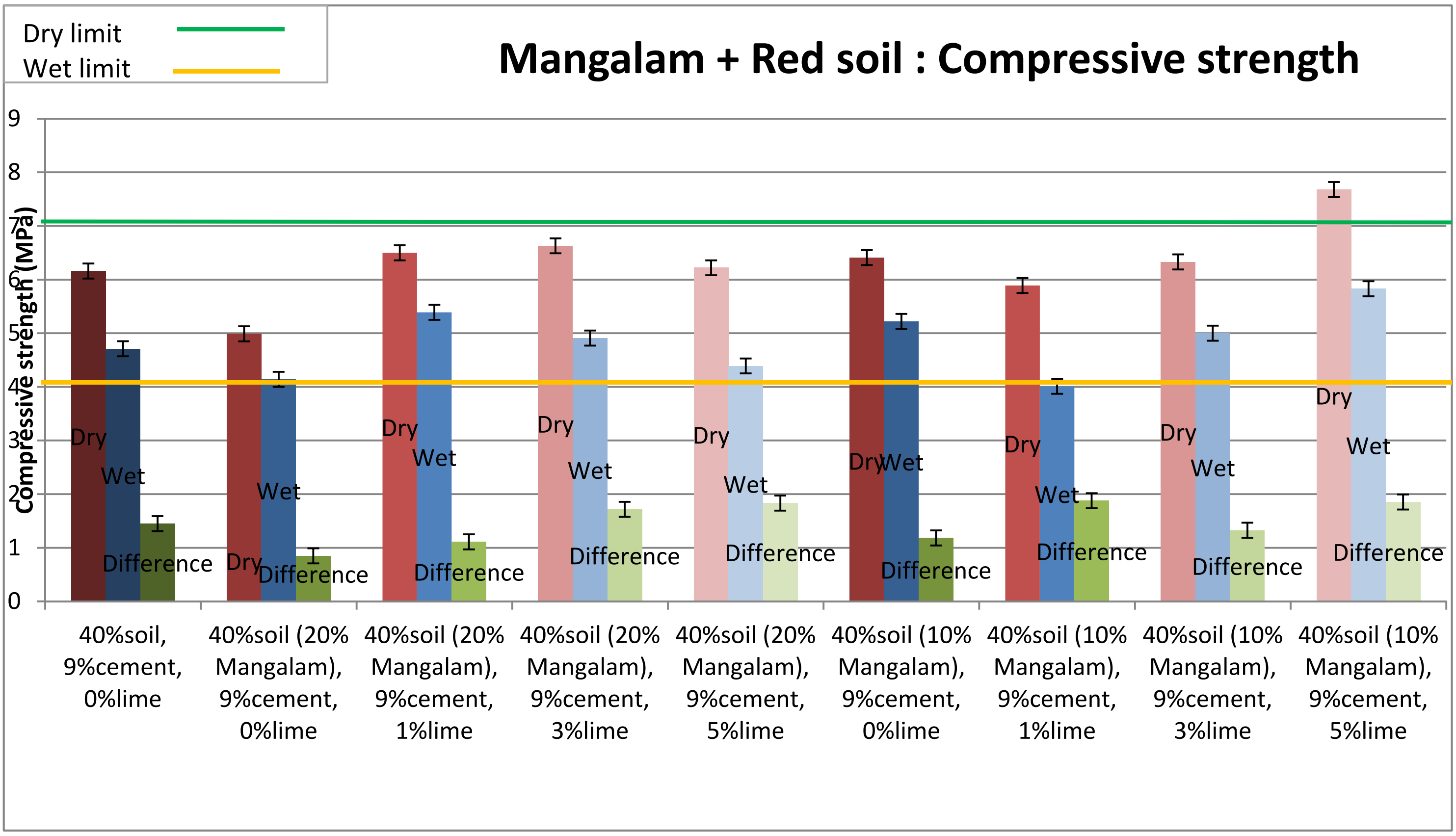
Graph 29: Shrinkage after the drying period (4 weeks of curing, then 1 week drying for samples without lime and 4 weeks for samples with lime) of Mangalam and Red soil samples (error=0.05%).

We have here three mixes over the limit of the acceptable shrinkage. One more time, it is pretty hard to have interpretation on the observable tendencies:

- The mangalam soil without lime seems to stabilize the shrinkage
- The addition of lime behaves differently according to the mangalam soil percentage
  - o With 20%mangalam soil, too much lime (from 3%) makes the mix shrink
  - o With 10%mangalam soil, lime makes the mix shrink but after 5% it stabilize the mix (so it is possible that the same point exist for 20%mangalam soil)

Picture 15: Example of Mangalm + Red soil beams (*40%soil_(10% Mangalam)_9%cement_5%lime*)

5.5.5 Compressive strength



Graph 30: Dry, wet and difference of compressive strengths of Mangalam and Red soil samples (error=0.1MPa).

Here again, we can link the compressive strength with the previous results, saying that a high density is linked with a low water absorption and a high compressive strength. For each and every mix here, it follows this law. This brings us to say that only one mix is reaching the good properties: *40%soil (10%mangalam), 9%cement, 5%lime.*

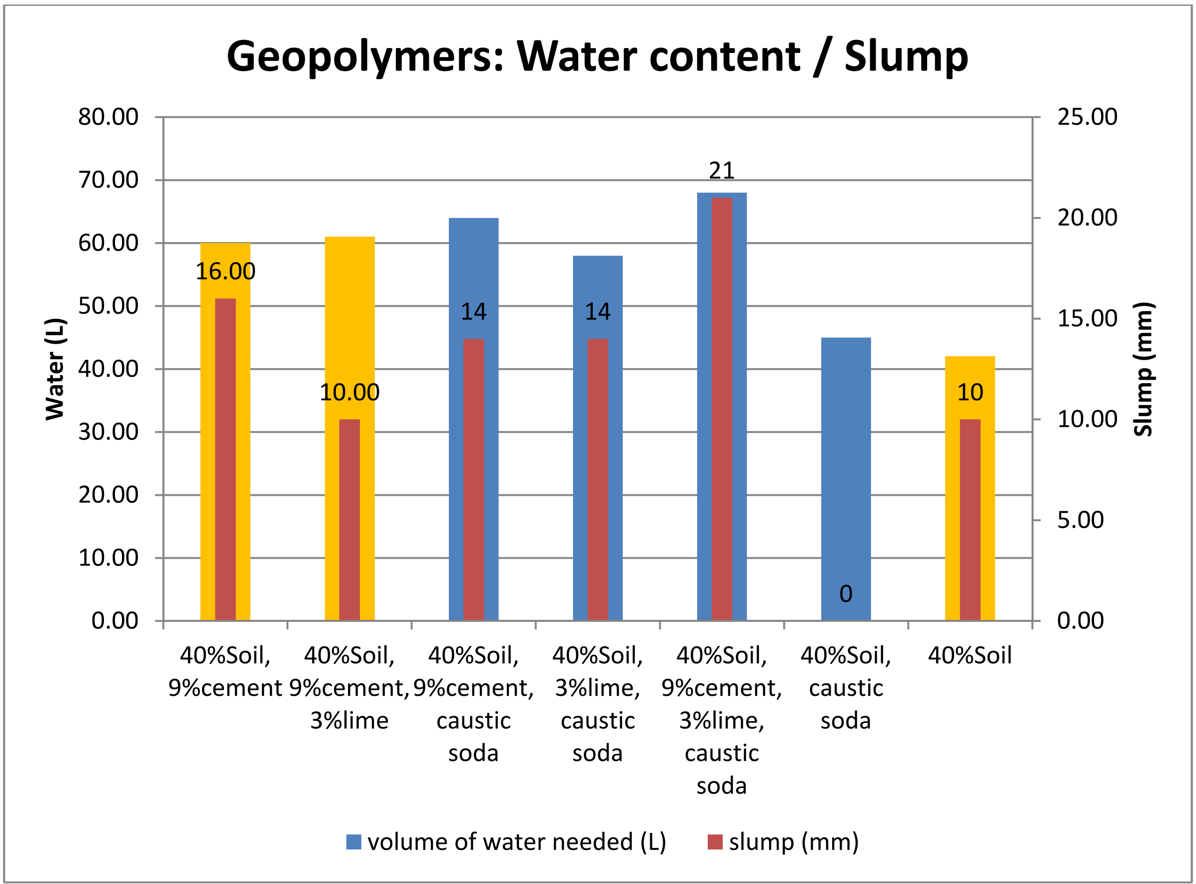
5.5.6 Conclusions

The Mangalam soil needs more attention, more studies to know how to use it. For example, we don't know if the influences that it is bringing to density, water absorption, shrinkage and compressive strength are because of the gradation or the different clay's behaviour.
It could be useful to know what kind of clay the mangalam soil is containing, in order to study its chemical reaction with lime for example, or explain why it behaves like that according to proportions or components.
Finally the last mix (*40%soil (10%mangalam), 9%cement, 5%lime*) is usable, but it contains a high percentage of stabilizers. We will see if we can improve these properties by the addition of fibers.

5.6 GEOPOLYMERS

The first idea to keep in mind here is that it was a try, to see if we can create geopolymers here, with the soil of Auroville. For this, a lot of hypotheses were made to calculate the quantity of caustic soda that we had to use, which a first reason to say that the following results have to be taken with great care. Moreover, this test has also been done to initialize real research on geopolymers' possibilities here in Auroville. The caustic soda has reactions with lime, cement and clay, so that we should observe these reactions with the different mixes done.

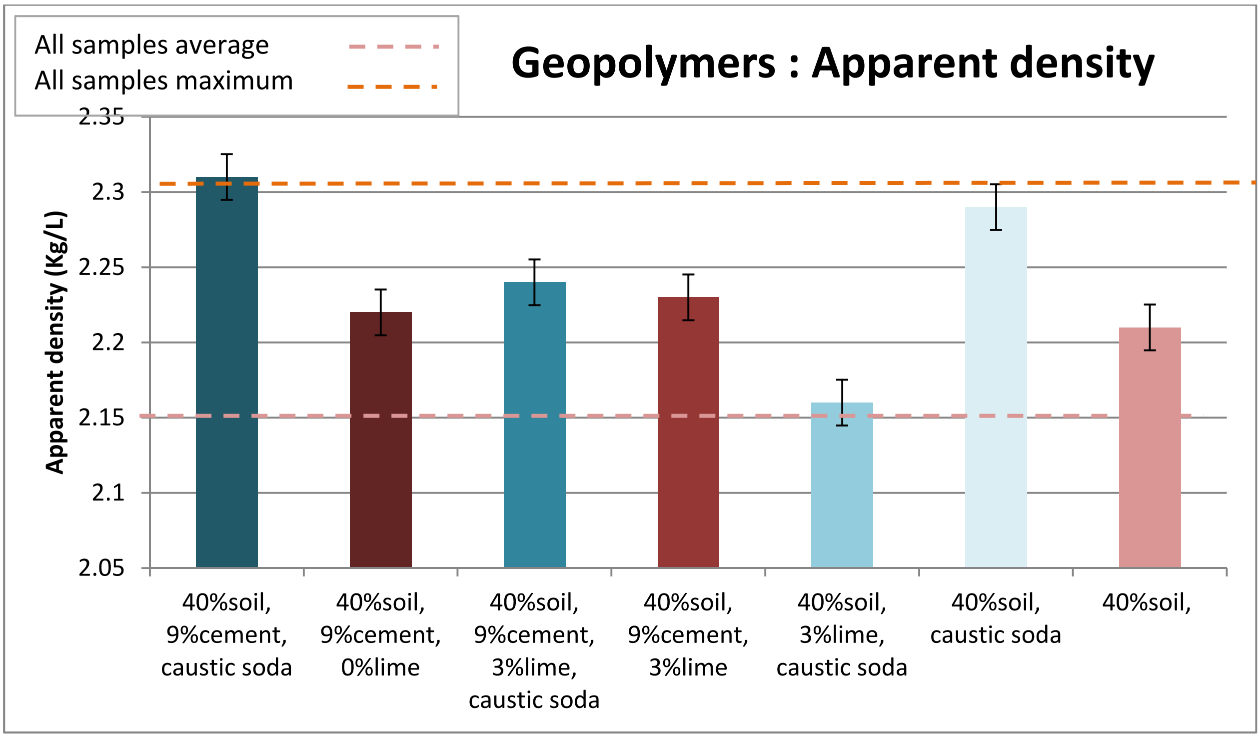
5.6.1 Water content and slump test



Graph 31: Water added during the casting of Geopolymers mixes+ its corresponding slump test (slump tests error=1mm and water measures error=1L).

Differences between the five firsts mixes (here on the graph 26) are not big enough to draw conclusions on the effect of caustic soda on the workability.
However, we can observe the fact that mixes without stabilizers don't need as much water as mixes with. The other curious fact is the slump of the "only soil" with caustic soda, is zero, which means that this mix should not workable at all. But it was actually workable, the cone for the slump should have moved but it did not. This can mean that the Earth Concrete was not well mixed.

5.6.2 Densities



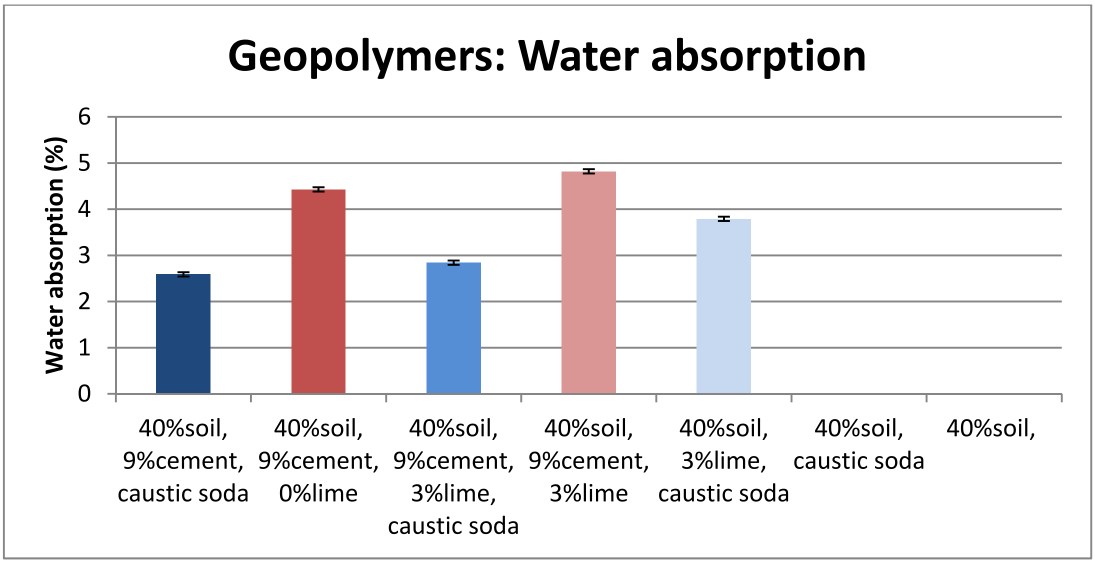
Graph 32: Apparent density of Geopolymers samples (error=0.02%).

Considering the densities, geopolymers mixes are within the best ones. We have two really high results here:

- The best one among all the samples is *40%, 9%cement, caustic soda*. It reaches 2.31kg/L. So here can be a first apparition of chemical reactions between caustic soda and other components. Firstly, it is much higher than the same mix without caustic soda. The question is: this reaction which created a denser material is with the clay, with the cement, or both?
- The second best density on this graph is, as curious as it can be, *40% soil with caustic soda*. This can eventually answer to the previous question, saying that, regarding the differences between these two mixes and the "*only soil*" mix, the caustic soda seems to have a huge effect on the clay. If the chemical reaction between them happens, it creates a geopolymer denser than every other mix.

Then, mixes with lime are quite worse. The mix *40%soil, 9%cement, 3%lime and caustic soda* is just a little bit denser than the same mix without caustic soda, which means that there is still some created geopolymers. But it is much less different than mixes without lime. When we look at the mix *40%, 3% lime with caustic soda*, it is really less dense than the same mix without lime and even less than only soil and aggregates. It seems that the lime has a counter interaction with geopolymers creation, or the reaction creates something that is very light compare to the rest of the mix.

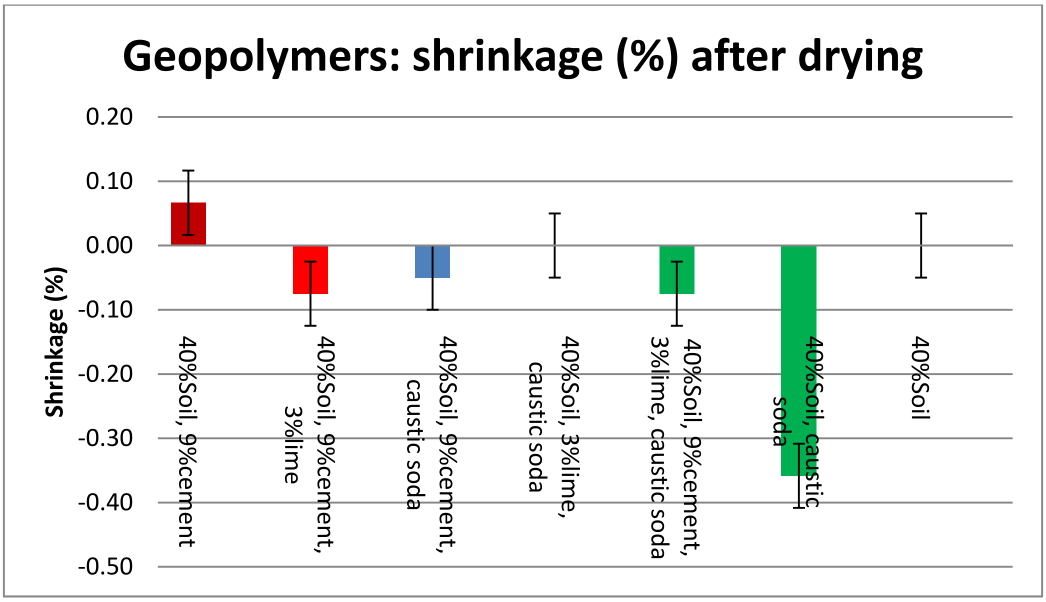
5.6.3 Water absorption



Graph 33: Water absorption capacity for Geopolymers samples (error=0.05%).

Here, there are no results for the mixes *40%soil with caustic soda*, and "*only soil*" mix, because their behaviour (too crumbly) was showing that they were not water resistant. So we could not soak them to see the water absorption, which actually could have been really high regarding the apparent porosity.
Secondly, caustic soda seems to act as a good waterproofing agent. It can be because of a good density, but for example, the *40%soil, 9%cement, 3%lime* with caustic soda did not have such difference in terms of density with its brother without caustic soda, while here there is quite a big difference between them in terms of water absorption capacity.

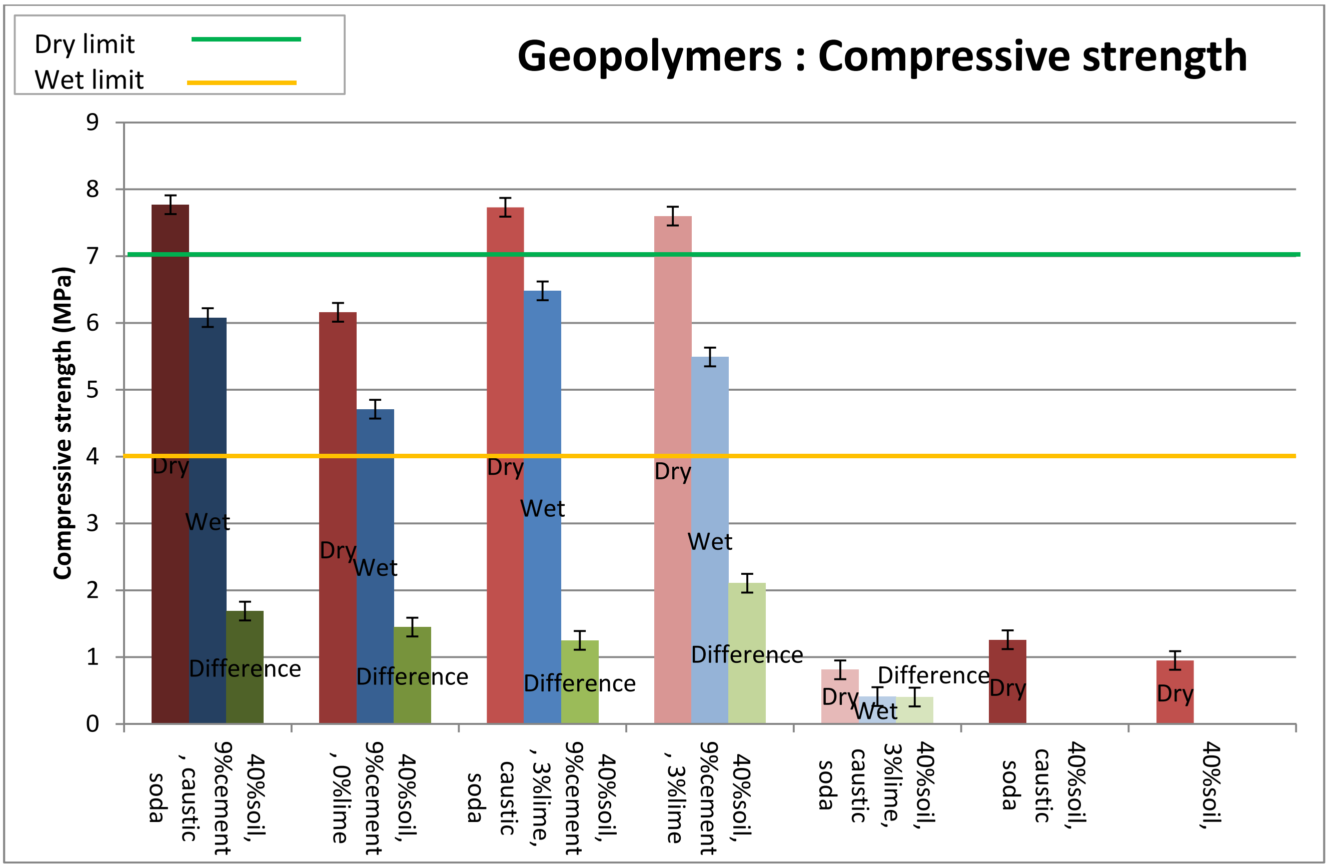
5.6.4 Shrinkage



Graph 34: Shrinkage after the drying period (4 weeks of curing, then 1 week drying for samples without lime and 4 weeks for samples with lime) of Geopolymers samples (error=0.05%).

Firstly, the two missing data about *40%soil, 3%lime with caustic soda* and *40%soil*, are not zero. It is actually because the shrinkage was too important for both of them that we did not report here the corresponding values.
For the other geopolymers mixes, like we saw before for densities and water absorption, caustic soda seems to act again as a good stabilizer (No apparent cracks, see picture 11 below).

5.6.5 Compressive strength



Graph 35: Dry, wet and difference of compressive strengths of Geopolymers samples (error=0.1MPa).

Here also, some really good results got out of the testing. Regarding the previous results, it is obvious that the compressive strength of the three last mixes (on this graph 30) could not be good.

Meanwhile, the previous results confirm also some of the good results that we have here.
On one hand, it is not really corresponding with previous results when we observe that mixes of *40%, 9%cement, caustic soda* and *40%soil, 9%cement, 3%lime, caustic soda* have really close compressive strength while their density was far one from the other. It may mean that the geopolymer created by the chemical reaction is lighter but stronger compare to the one created by the clay reaction.
On another hand, for the *40%, 9%cement, caustic soda* mix respects expectations: the fact that it has a good density, low water absorption and a low shrinkage is related to the fact that it has good compression strength.

Picture 16: Example of geopolymers beams (*40%soil, 9%cement, 3%lime, caustic soda)*

5.6.6 Conclusions

Geopolymers have, for a first try here at the AVEI, a promising future. Several mixes done reach wanted properties, and mostly thanks to the addition of caustic soda. It is here obvious that researches on geopolymers should be deeply studied:

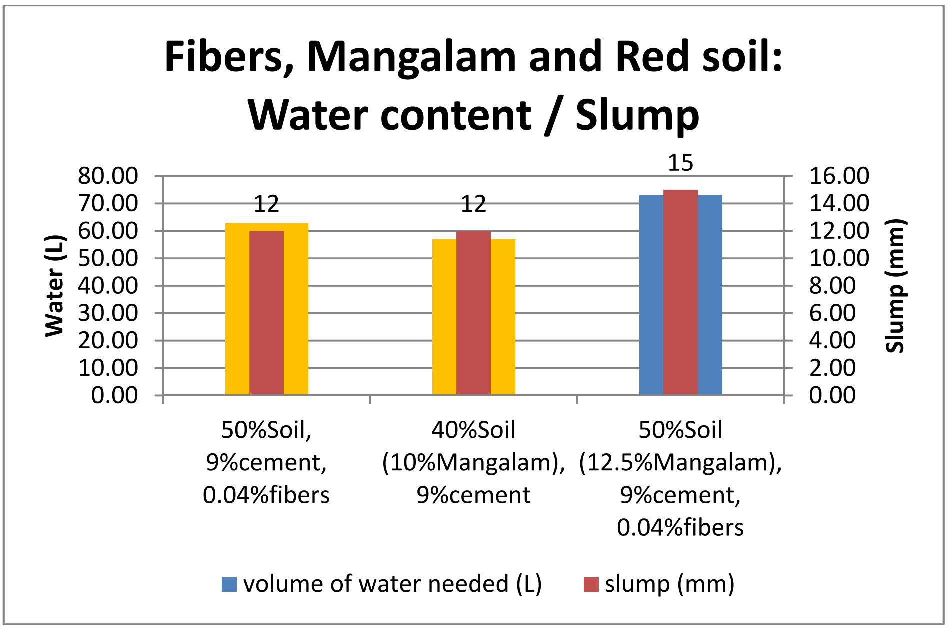
- First of all, the quantities of caustic soda used during the casting must be checked. Because they are based on hypothesis, other calculation and other quantities should be tried in order to find the best one.
- Each possible chemical reactions should be studied more and more, in order to know better if the caustic soda is able to react with all the components with it supposes to happen (Which one come in first, which one is the best one to point out, …)

But, in our case, there is an important limit with geopolymers: the use of caustic soda. This product is very dangerous and we had to wear a lot of protection during the casting, which is not convenient at all. Moreover, it was for us kind of in contradiction with the fact that we try to reach sustainable building, which include health topics. Thus, a study should be done on this subject in order to know if we can find (as the Egyptians did for the pyramids) natural products to produce caustic soda during the casting, and if the caustic soda that we actually use can be considered as a "low-consuming" product.

5.7 MANGALAM SOIL + RED SOIL AND FIBERS

This mix was done during a waiting period between the end of the "only-cement-containing mixes" curing period and the one of lime-containing mixes. The first results were not really good, so it was done to mix two "good behaviour" mixes (*50%soil, 9%cement, 0.04%Fibers* and *40%soil (10% Mangalam),9%cement*), in order to reach the wanted properties. A low percentage of mangalam soil seemed to bring almost good results and same for a few litters of fibers, so here we tried to mix them.

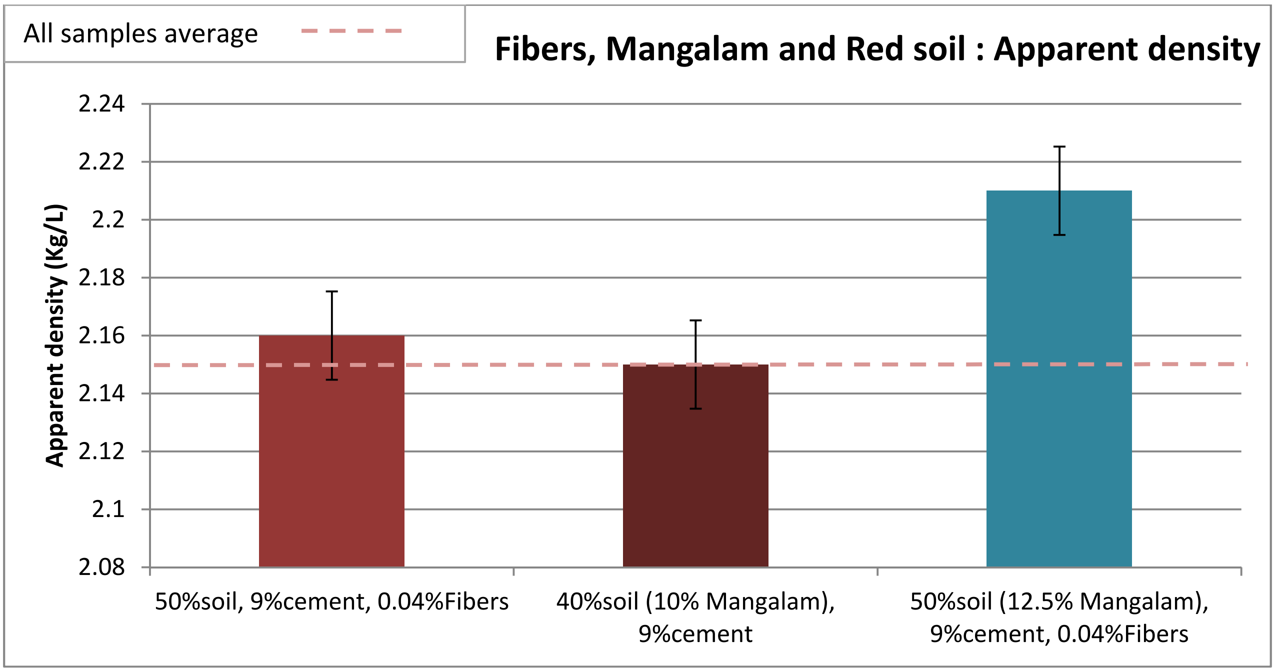
5.7.1 Water content and slump test



Graph 36: Water added during the casting of Geopolymers mixes+ its corresponding slump test (slump tests error=1mm and water measures error=1L).

In terms of water content, our mix "*50%soil (12.5% Mangalam), 9%cement, 0.04%Fibers*" needed more water than its two reference mixes. The point is that fibers mixes need more water to bring the workability lost by the addition of water, and the Mangalam soil mixes need also more water (see part 5.5.1 p50). This interpretation is to take with care, because the slump test (even if it is not accurate) has also different values (to really compare, we should have same slump test and different water contents).

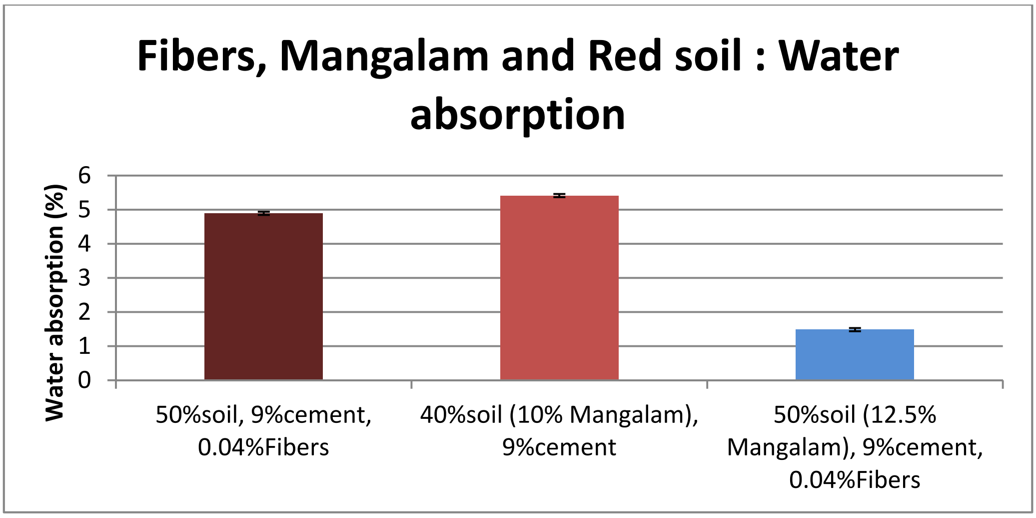
5.7.2 Densities



Graph 37: Apparent density of Fibers, Mangalam and Red soil samples (error=0.02%).

While the reference samples have an average apparent density, our studied mix (*50%soil (12.5% Mangalam), 9%cement, 0.04%Fibers*) has a really good one. The question is, how can it be possible while fibers AND Mangalam soil are supposed to decrease the density? Looking at previous results (see part 5.2.2 p39 and 5.5.2 p51), it is also possible that these additives increase the density. Indeed, their effect should be more studied.

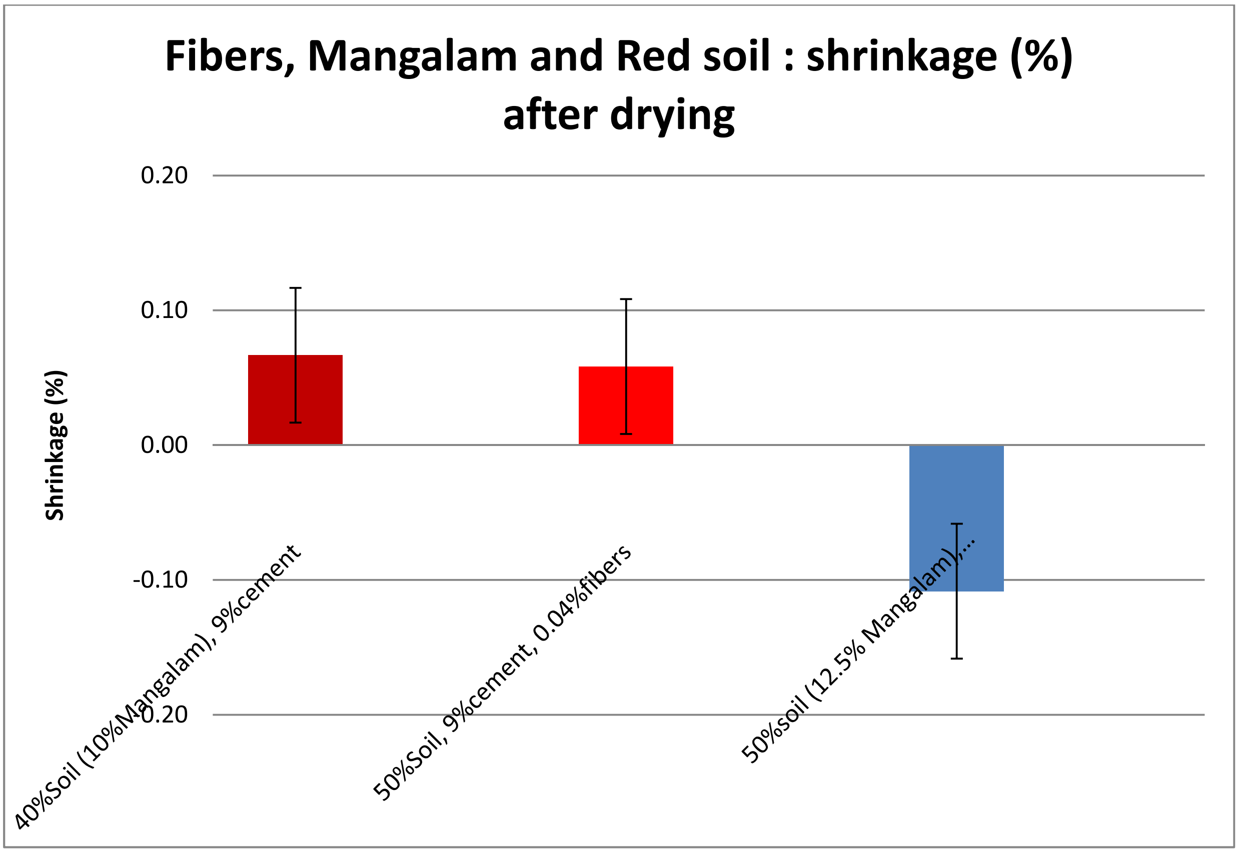
5.7.3 Water absorption



Graph 38: Water absorption capacity for Fibers, Mangalam and Red soil samples (error=0.05%).

Regarding the previous graph (densities), water absorption capacities correspond to the fact that, the denser is the concrete, the lower is the water absorption. One more time, this mix of fibers, Mangalam and Red soil is contradicting the previous results for Mangalam soil mixes, saying that this soil is increasing the water absorption. On another hand, a little quantity of fibers was decreasing it. Indeed, we see here that the mix of both fibers and Mangalam soil has a reaaly good effet on density and water absorption. Should it be because of the clay content of Mangalam soil, the water added in the mix, or a combination of both facts?

5.7.4 Shrinkage



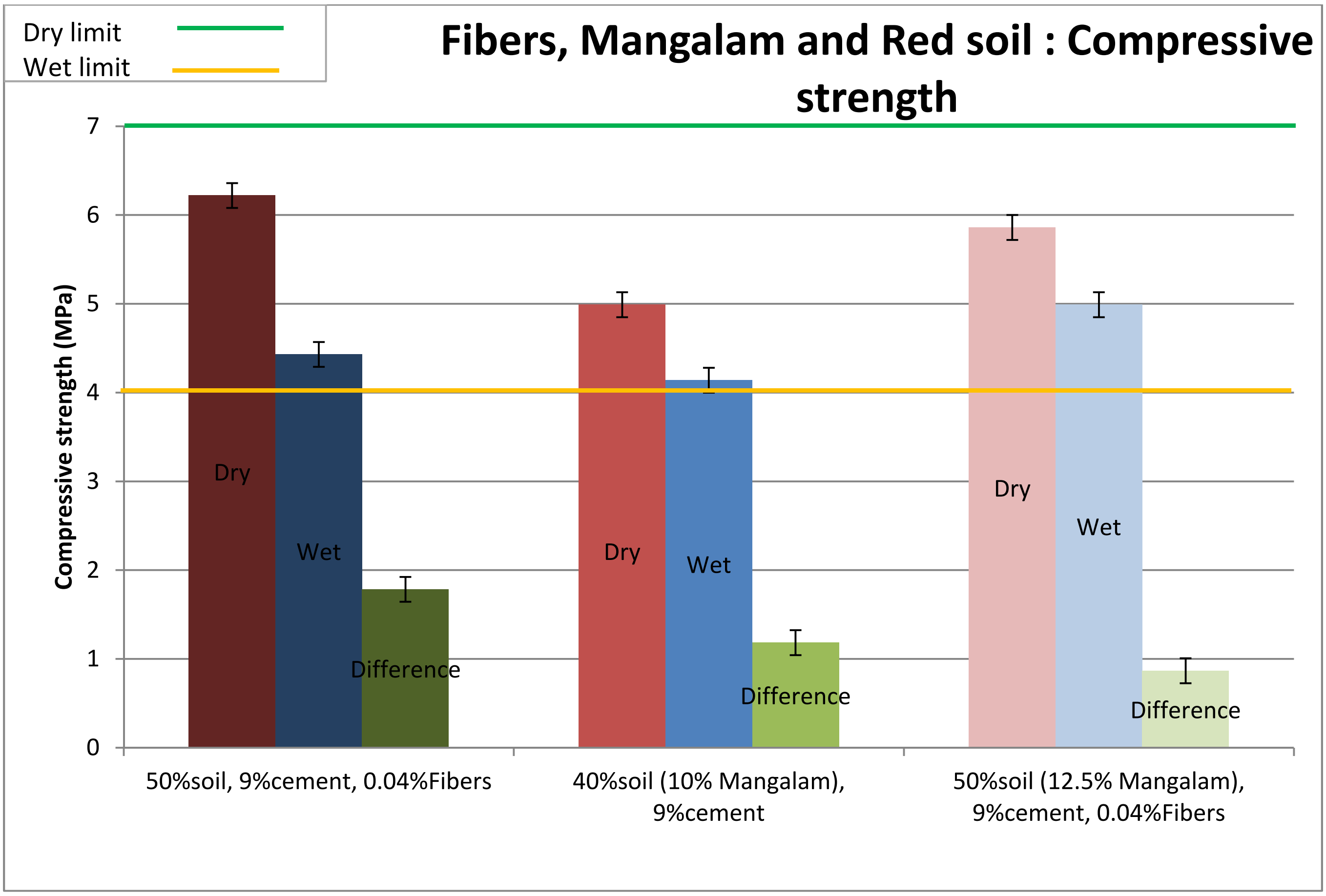
Graph 39: Shrinkage after the drying period (4 weeks of curing, then 1 week drying for samples without lime and 4 weeks for samples with lime) of Fibers, Mangalam and Red soil samples (error=0.05%).

Like it was presented before (see part 5.1.4 p35), some mixes have positive shrinkages due to wrong timings or due to the clay content of the mix. Both reference mixes have positive shrinkage, while our test of mix of fibers, Mangalam and Red soil is negative and, moreover, it goes over the limit of -0.1% of the total length.

On one hand, it seems that fibers did not have effect on the shrinkage (to reduce it). On the other hand, the composition of the mix, especially the clay content, might gave a strong shrinkage (see cracks on the following picture)

Picture 17: Cracks on Fibers, Mangalam and Red soil beams.

5.7.5 Compressive strength



Graph 40: Dry, wet and difference of compressive strengths of Geopolymers samples (error=0.1MPa).

Finally, this test is not conclusive. It was thought possible that the combinaision of two interesting mixes could have given a mix which reaches the wanted properties. But knowing that we don't know the possible chemical reactions due to the clay content of the Mangalam soil, or we don't know if it is still active in spite of the cement content, or its behaviour according to the added water, we could not have good expectations for this mix.

The mix (50% soil (12.5% Mangalam), 9%cement, 0.04%fibers) does not reach 7Mpa of dry compressive strength, but on another hand we observe a low difference between dry and wet compressive strength.

5.7.6 Conclusions

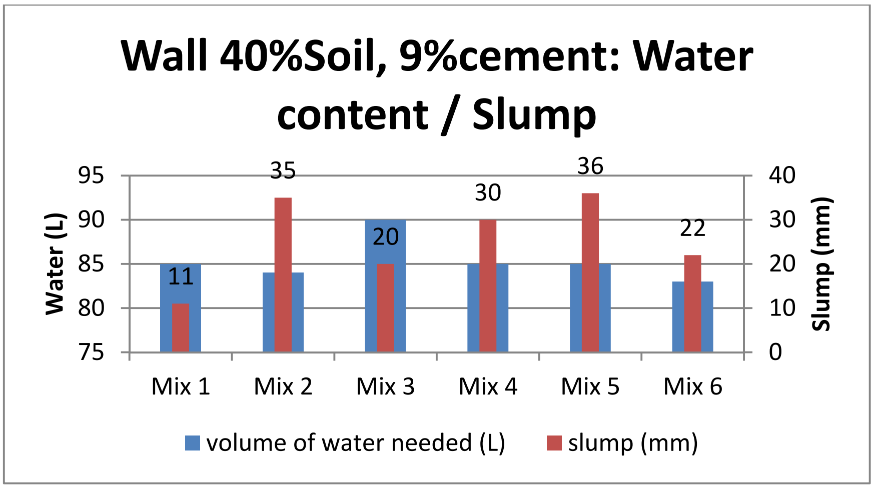
To conclude on this try, one more time, a lack of knowledge on different parameters (particularly for the clay) prevents us to have good expectations and good interpretations. So, it could be interesting to go deeper in soil analyses and additives analyses to be able to explain those facts.

By the way, the fact that the mix of fibers and mangalam soil improved a lot the density is a curious fact that has to be more explained.

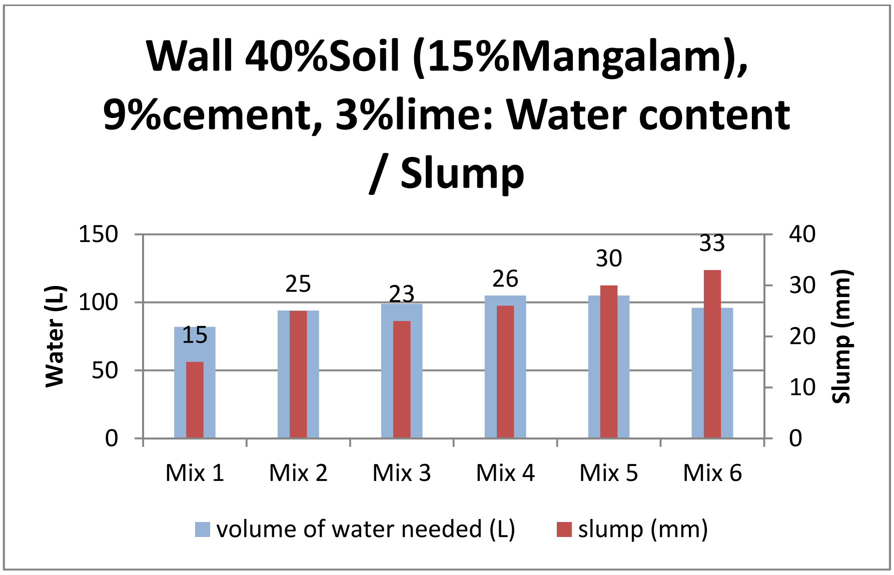
5.8 WALLS

Here is just a presentation of the walls' results, but a complete report was written about them. So, for more details about the mix choices, the formwork, the casting and observations, refer to this report (29).

5.8.1 Water content and slump test



Graph 41: Water added during the casting of first wall mixes+ its corresponding slump test (slump tests error=1mm and water measures error=1L).

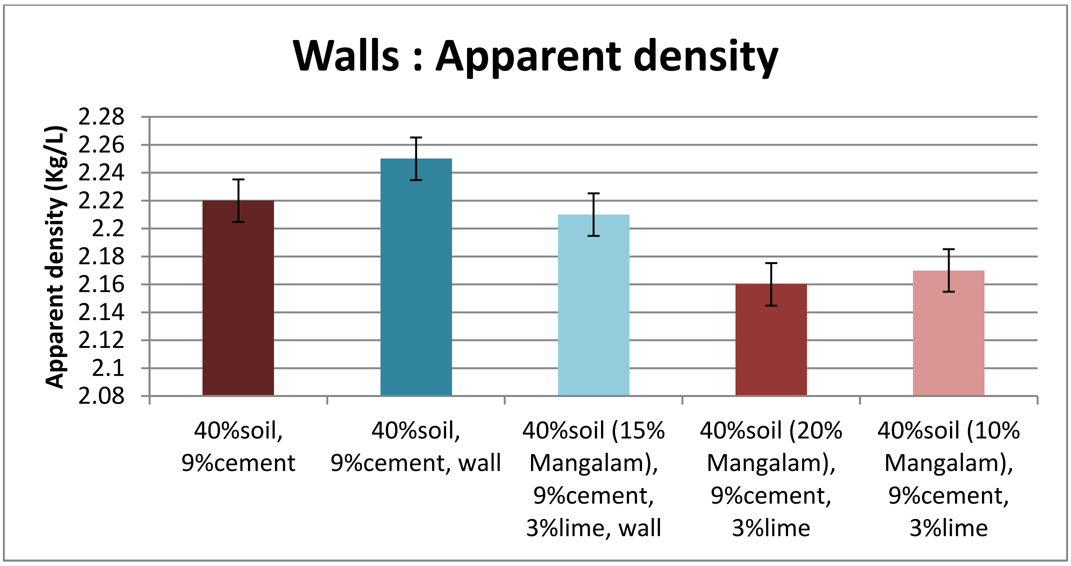


Graph 42: Water added during the casting of second wall mixes+ its corresponding slump test (slump tests error=1mm and water measures error=1L).

In general, the first observation is that the second wall needed much more water for its mixes than the first one. It is linked with the experience we had with samples of other mixes during the research (30), lime and Mangalam soil both need more water than other mixes.

Secondly, for the two walls, the first mix has a low slump because of the fact that we are at the beginning searching for the best workability to pour the concrete. Then, for the first wall, the slump is really variable, while it is almost constantly increasing for the second one. The slump test is hard to trust and interpret because of the fact that is never done in the same way. But, on another hand, the weather was really hot those days so the temperature was obviously influencing the needed water and the workability as well.
Finally, considering the all research (30), we added more water than we did for the corresponding mixes because of the weather and the fact that we had to mix on the ground.

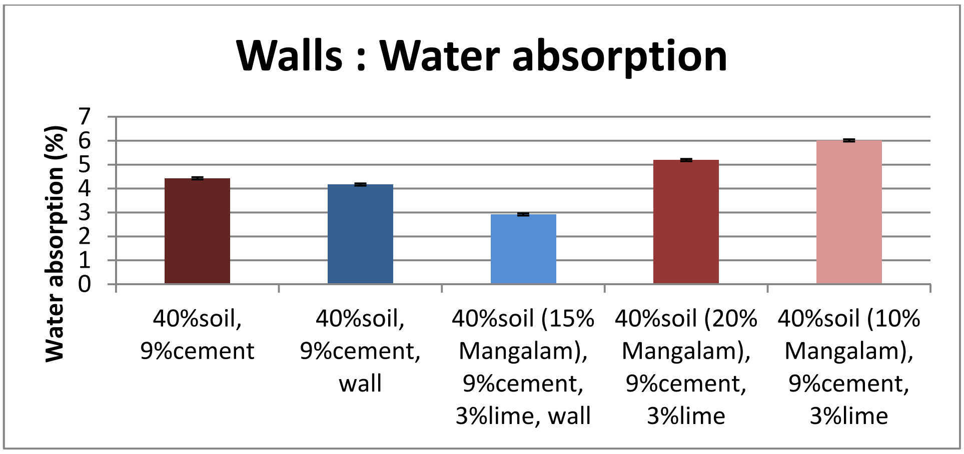
5.8.2 Densities



Graph 43: Apparent density of walls samples (error=0.02%).

Both walls samples have better densities than their corresponding mixes done during the research. The main apparent reason can be, as we saw previously, the difference of added water. Because the mixes had better workabilies in order to be better poured, they were better vibrated which bring a better densities. Then, the first wall (40%Soil, 9%cement) has a higher density than the second (40%Soil (15%Mangalam), 9%cement, 3%lime). We also saw during the research, and as we can see it here, that Mangalam soil as lime decreases the density for certain percentages. Here both percentages of Mangalam soil and lime are too high to increase the density and have the opposite effect.

5.8.3 Water absorption



Graph 44: Water absorption capacity for Fibers, Mangalam and Red soil samples (error=0.05%).

Corresponding to the previous results about densities, water absorption capacities are low by the way that their densities are high. But we observe a curious fact: the second wall (40%Soil (15%Mangalam), 9%cement, 3%lime) has a lower water absorption capacity than the first one (40%Soil, 9%cement), which is not in accordance with the densities results. During the research, we did not observe any behaviour like this for Mangalam and Red soil mixes, so it should be not about additives. One explanation could be that, because we add more water than corresponding mixes during the research, additives had better chemical reactions, and it is possible that lime created some kind of light particles networks which have a waterproofing power.

5.8.4 Shrinkage

	1 week	2 weeks	4 weeks	5 (cement only) or 8 weeks (+lime)	shrinkage (%) after drying
40%soil, 9%cement, wall	-1.0	-1.0	-1.0	-2.0	**-0.04**
40%soil (15% Mangalam), 9%cement, 3%lime, wall	-1.0	-0.5	-1.0	-1.0	**-0.02**

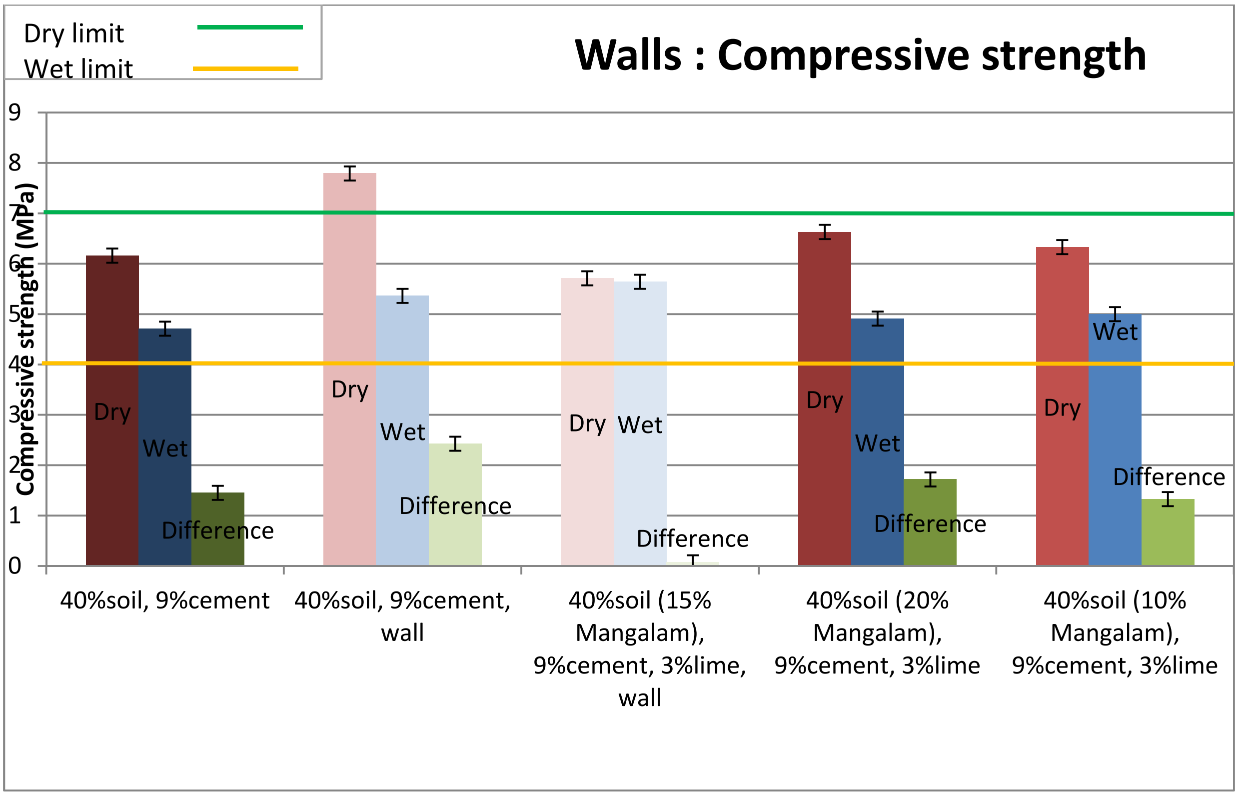
Table 8: Walls shrinkage (error=0.02%).

Firstly, walls permit a better observation of the shrinkage. We measure few millimetres on a 5m long sample, so the error is more acceptable than on beams.

The results here are good, they show a low shrinkage. But these results have to be really taken with care:

- Only one measure (one place on the wall, on the top, on the smoothed surface) was done for each wall, while several measures could have been done on sides (even if it is after the formworks removal).
- It is possible that, finally, we cannot really observe the shrinkage on long samples like that. They will never move more than that. Because the shrinkage act at a microscopic scale while we are observing it at a macroscopic scale. That means that shrinkage creates cracks in this 5 meters experimented surface, so there are movements within these 5 meters, but the 5 meters will not move.

5.8.5 Compressive strength



Graph 45: Dry, wet and difference of compressive strengths of walls samples (error=0.1MPa).

Firstly, let's observe the first wall's results (40%Soil, 9%cement). Density's and water absorption's results were good. So here, because it is linked, the compression strengths' results are good also (it reaches the wanted properties easily). Indeed, it seems that because we add more water, all the results are better than the corresponding mix done during the research.
Secondly, the second wall's results (40%Soil (15%Mangalam), 9%cement, 3%lime) are quite curious. The dry and wet compressive strengths results are almost the same. Can we say that, because samples were put into the water during 48 hours to saturate them, chemical reactions of hardening continued like in a curing process? Or it is just because the water absorption was not high, water did not affect the compressive strength? Or also, it is possible that samples were not saturated at all, so that samples were still dry inside.
Nevertheless, the results of this second wall are lower than there are supposed to be according to the other samples done during the research. Indeed, this mix had good density and water absorption, but the compressive strength does not reach wanted properties. This can also be because of the added water which could have been in a too high quantity.

5.8.6 Conclusions

Poured Earth Concrete research has been through a good step here by doing one scale experimentation. This test gives a lot of next steps to do in order to keep improving this technique:

- Keep observing these walls through the time to note their behavior.
- Find a way to see if the apparent cracks are weakening the all wall or if they are just on the surface.
- Find a way to avoid big bubbles.
- Design adapted formworks for the Poured Earth Concrete technique.
- Observe the improving of times and costs of a PEC wall's casting by using other equipment (adapted formwork, mixing maching…).
- Study and find the best water proportion to use according to previous results.

6. CONCLUSION

To conclude, this research gave an important amount of promising results. Numbers of tests done (such as the sieving and hydrometric tests, compression test on only three samples) are actually not as accurate as we should need, but we have now some interesting directions to continue this research.
We can almost say that we should know be able to build some kinds of buildings which does not need high properties for the building material. This is a really encouraging fact.

On thirty-five mixes, eight of them reach all the needed properties. And only one of them contain 50% of soil. Here is the list of these successful mixes:

- 40%soil_9%cement_1%lime
- 40%soil_9%cement_3%lime
- 40%soil_9%cement_5%lime
- 50%soil_9%cement_1%lime
- 40%soil (10%mangalam), 9%cement, 5%lime
- 40%, 9%cement, caustic soda
- 40%soil, 9%cement, 3%lime, caustic soda
- 40%Soil, 9%cement (from the wall)

One scale tests have been done in order to see the facility, the rapidity and the cost-efficiency of this technique. First, as it was presented before in this report, walls were poured. Thanks to this, we can evaluate many parameters which then permit to optimize future tests but also help for a real case construction. Secondly, a road was done (see \\192.168.0.1\Research Projects\R&D 04 Poured Earth\06 Reports\2014 Léo Boulicot & Théo Vinceslas\Road\Road report.docx) with the same technique, comparing usual concrete road to design an earth concrete one. All the details are the report, and give ideas about the behaviour of an Earth Concrete for road application.

For all the next steps suggested by this research, see \\192.168.0.1\Research Projects\R&D 04 Poured Earth\06 Reports\2014 Léo Boulicot & Théo Vinceslas\Next steps\Summary works already done.docx:

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APPENDIXES

Appendix 1: HYDROMETER PROTOCOL (22)

1) K value according to the temperature

Temperature (°C)	K	Temperature (°C)	K
16	0,01435	27	0,01258
17	0,01417	28	0,01244
18	0,01399	29	0,0123
19	0,01382	30	0,01217
20	0,01365	31	0,01192
21	0,01348	32	0,01176
22	0,01332	33	0,01161
23	0,01317	34	0,01145
24	0,01301	35	0,01130
25	0,01286	36	0,01114
26	0,01272		

Table 9: K values according to the temperature (16 to 36 °C)

2) Relation between R read on the hydrometer and L its effective depth:

hydrometer reading R	effective length L	hydrometer reading R	effective length L	hydrometer reading R	effective length L	hydrometer reading R	effective length L
0	16,3	16	13,7	31	11,2	46	8,8
1	16,1	17	13,5	32	11,1	47	8,6
2	16	18	13,3	33	10,9	48	8,4
3	15,8	19	13,2	34	10,7	49	8,3
4	15,6	20	13	35	10,6	50	8,1
5	15,5	21	12,9	36	10,4	51	7,9
6	15,3	22	12,7	37	10,2	52	7,8
7	15,2	23	12,5	38	10,1	53	7,6
8	15	24	12,4	39	9,9	54	7,4
9	14,8	25	12,2	40	9,7	55	7,3
10	14,7	26	12	41	9,6	56	7,1
11	14,5	27	11,9	42	9,4	57	7
12	14,3	28	11,7	43	9,2	58	6,8
13	14,2	29	11,5	44	9,1	59	6,6
14	14	30	11,4	45	8,9	60	6,5
15	13,8						

Table 10: Effective length deduced from R read while experimentations

Appendix 2: VISUAL SEDIMENTATION CONCLUSIONS

Picture 18: red soil sedimentation, after 1h

Picture 19: Mangalam soil sedimentation, after 30min

Picture 20: both sedimentations after 1month

Picture 10 and 11 show the behaviour of thin particles of Red (after 1h) and Mangalam soil (after 30min) sedimentation in hexametaphosphate solution. We can see that the Mangalam soil seems to sediment faster than the red soil. However, at these moments, hydrometer sinks more in the red soil solution than in the Mangalam soil solution. That means in picture 11 there are less particles deposited in the same volume as picture 10. Picture 12 shows sedimentation after 1 month. The red soil seem to be more compacted than after 1h (picture 10) even though the Mangalam soil sedimentation is not really modified. We can also remark that the red soil solution is less cloudy than the Mangalam one; it could be due to the particles concentration in the solution.

Appendix 3: SPECIFIC DENSITY PROTOCOL (for solids into water, not reactive with water, not water dissolvable, which sink into water) (4), (31):

- Choose a recipient depending on the size of the biggest aggregate. A proposition of calculation for this size is given below. Tare the recipient.

➢ *Recipient size[9]:*

$$RV = \frac{nb_{agg} * l_{agg}^3 * \pi}{6000000 * MC}$$

RV: Minimum recipient volume (L)
l_{agg}: greater length of the coarsest aggregate (mm)
MC: Maximal compactness (here 0.74)
nb_{agg}: Approximate number of aggregates into the chosen recipient

$$M_D = 5 * l_{agg}$$

M_D: Minimum diameter of the recipient (mm)

- Fill the recipient with water. Weigh water, note the temperature of water.
- Empty and dry the recipient.
- Fill the recipient with the dry sample (dried during a night in an oven, temperature = 90°C). Weigh the dry sample.
- Complete the recipient containing the sample with water and shake all to avoid air bubbles. For the shaking, the use of a vibrating table permits to be more accurate. Note the mass.
- One measure is enough to have 2g accuracy.

➢ *Specific density of each aggregate size:*

Calculations come from (4)*. Some modifications have been added.*

$$\rho_{agg} = \frac{m_D * \rho_w(T)}{m_D + m_W - m_{WA}}$$

ρ_{agg}: Specific density of the aggregate (g/L)
$\rho_w(T)$: Specific density of water (g/L) at the temperature T (°C)
m_D: Mass of the dry aggregate and the recipient (g)
m_W: Mass of the water and the recipient (g)
m_{WA}: Mass of the aggregates, the water and the recipient (g)

[9] In order to determine the smallest recipient usable, different hypothesis are selected:

- This calculation is applied on divided solid, as sand, usually modeled by spheres.
- This calculation relies on the sphere packing theory. Identical spheres, arranged to have the best compactness (34), are contained into a volume equal to 1/0.74 of the sum of spheres volumes.
- We consider that aggregates are spherical diameter equal to the greater length.
- We consider that an accuracy of 0.5% is enough. This accuracy corresponds to have more or less 1 aggregate on the total theoretical number of aggregate.

Appendix 4: BULK DENSITY PROTOCOL (4)

- Choose a recipient with a perfectly known volume (see appendix 3 p.43 to know the corresponding protocol)
- Tare it.
- Add the matter as done onsite (for example, the coconut fibers are dry, approximately 7cm length, non-sort-out, and pressed as well as possible by hand whereas the Mangalam soil is just poured into the recipient).
- Weight all.

Determine the bulk density as: $bulk\ density = \frac{matter\ mass}{recipient\ volume}$

- Do this protocol 3 times and calculate the average, in order to have a more accurate result.

Appendix 5: MATERIALS CARACTERISTICS and ADDITIONAL MIXES PREPARATION

- Cement
- Brand: Ramco
- 28 days strength: 24MPa
- 1bag ⇔ 50kg
- Bulk density: 1.06Kg/L (13)
- Quantity: 9% (not change for mixes using cement)

- Red soil
- Features are given in part 3.1 p.25, after doing characterisation tests.
- Bulk density: 1.23kg/L (25)
- Quantity: 40% or 51%[10].
- Additional treatment: the soil is crushed before used, in order to separate blocks sampled into the ground.

- Red soil and Mangalam soil
- Features are given in part 3.1 p.25, after doing characterisation tests.
- Mangalam soil bulk density: 1.27kg/L
- Quantity:
    - 9% of Mangalam soil and 30% of Red soil
    - 18% of Mangalam soil and 20% of Red soil
- Additional treatment: the soil is crushed before used, in order to separate blocks sampled into the ground.

- Gravels and pebbles

Gravels and pebbles used are from a rock named "blue metal" (type of basalt used in this part of India).

- Sizes: ½", 1" and 2" (12.7mm, 25.4mm, 50.8mm) according to density tests done (28)
- Bulk densities: ½": 1.34kg/L, 1": 1.52kg/L and 2": 1.4kg/L
- Quantities (same order as above):
    - With 40% of: 13%, 32%, 16 (17 with Mangalam soil)%
    - With 50% of: 0%, 26%, 24%

[10] Different gravels and pebbles proportions change depending on the quantity of soil (according to the best mix density wanted part 2.2.3 p.19)

- ❖ Lime

The lime used is:

- Brand: Ramco
- Hydraulic lime
- 1bag ⬄ 40kg
- Bulk density: 0.55kg/L (13)
- Quantity: for each series with lime, 4 quantities are tested: 0%, 1%, 3% and 5%

- ❖ Coconut fibers
- Dry
- Average length: around 5cm
- Separated one from each other
- Bulk density, measured after being pressed in a 1 litre recipient: 0.081kg/L (appendix 4 p.44)
- Quantity: for the series with coconut fibers, 3 quantities are tested: 0.04%, 0.08%, 0.16%
- Added just after mixing the thin particles together, big aggregates are added and all is mixed again.

- ❖ Lime and Alum Paste (LAP)

Alum is (13):

- ammonium sulphate which composition is:
  - o 11.20% Aluminium Oxide Al_2O_3,
  - o 37.56% Aluminium sulphate as $Al_2(SO_4)_3$,
  - o 0.13% Potassium Sulphate as K_2SO_4,
  - o 14.50% Ammonium Sulphate as $(NH_4)_2SO_4$,
  - o 0.002% Water Soluble iron as Fe,
  - o 36.608% Water of crystallization.
- Crushed by hand and sieved with a 2mm mesh sieve
- Bulk density for 2mm powder = 0.862g/L (13).
- Solubility in tap water: around 100g/L (see appendix 6, p.49)
- Quantity: 100g of alum per litre of water needed (10.0% in mass percentage of the water needed at 30°C) in order to have a saturated solution (13).

Lime: see above.
Lime and Alum Paste is prepared as following (13):

- Preparation of alum water:
  - o Estimate quantities of water needed for the paste but also for the mixing of the mix, pour it into a big enough recipient (we consider that the volume of alum is negligible when added into water).
  - o Add the alum, stir well at least during 5min (see appendix 6, p.49), check if all alum is dissolved, and even so continue to stir.

Every worker mixing LAP has to wear a mask with cartridge for ammonia and goggles well tight.

- Paste preparation:
  - o Prepare the paste the day before using it.
  - o Pour 3 volumes of water per volume of lime (quantity of lime used corresponds to the percentage needed in the mix) used into a big enough recipient.
  - o Add slowly the lime, crushing lumps as shown on picture 13.

- Cover it to avoid water evaporation.
- Sample mixing:
  - Paste is added after mixing all the dry mix (aggregates and additives, watch picture 13 below).
  - Additional alum water is used if needed instead of water.


Picture 21: LAP mixing and adding in the dry mix

- ❖ Homeopathic Mix of Lime and Alum (HOMLA)

Additives used are the same as in LAP (13). Only proportions change:
- Alum: 100g of alum per litre of water needed.
- Lime: 73L (1bag) for 500L of water.

Alum water is made as for LAP:
  - Estimate quantities of solution (HOMLA) needed for the mix: all the water added in the mix will be replaced by this solution.
  - Pour the equivalent quantity of water into a big enough recipient (we consider that the volume of alum and lime is negligible when added into water).

Solution preparation:
  - Prepare the solution the day before using it.
  - Add slowly the quantity of lime needed, crushing the lumps, in order to have a solution well mixed.
  - Cover it to avoid evaporation.
  - Use this solution instead of water in the mix.

- ❖ Geopolymers

According to (16) and (15), the solution of caustic soda added to the mix is less than 3% concentrated, which corresponds to a dangerousness minimal during its use (32), however, cautions must be taken by workers mixing it. In another hand, full protection (avoiding contact with skin, eyes or mucus membrane) must be worn by people preparing the solution, knowing that they use solid caustic soda. Do not use aluminium recipients.

Caustic soda:
- Sodium hydroxide NaOH
- Solid with a slab shape
- Bulk density measured (see appendix 4, p.44): 0.860kg/L
- Solubility in water (33): 1090g/L at 20°C
- Quantity: 1L of soda per 186.7L of soil calculations given in appendix 7, p.50. It means 0.15% when used.

Solution preparation:

- Estimate quantity of water needed for the mix. Estimation must be done in order to use all the solution into the mix, adding tap water if needed at the end. Try also to have enough water in order to have a solution of maximum 3% of caustic soda (see appendix 7, p.50 to know the calculation of this percentage) to prevent risks on health (32).
- Pour this water in a big enough recipient.
- Add the caustic soda slowly, carefully while mixing it, in order to avoid spatter and quick solution heating.
- This solution can be used just after being prepared, instead of water in the mix.

Appendix 6: ALUM SOLUBILITY IN TAP WATER:

1) Solubility of crushed alum (particles size ~2mm) in water.
- In a beaker, pour 500mL of water, temperature around 30°C
- Add 10.0g of alum in the beaker
- Stir the solution with a magnetic stirrer during 1min
- Check if alum powder is fully dissolved.
- Add 10.0g of alum a repeat the following step until you can see alum powder in the bottom of the beaker.

Conclusion: after adding 60.0g of alum, 10.0g by 10.0g and stirring each time 1min, a few of alum left in the bottom of the beaker. So we decide to consider that 50.0g is the solubility limit, considering that we will prepare big quantities (around 200L by mix) by mix and considering that hand stirred will be more complicated to stir well.

2) Time needed to solubilise the full quantity in one time.
- Pour 500mL of water in a beaker, same temperature as above
- Pour the whole quantity of alum determined above (here 50.0 g)
- Stir as it was done above and note the time needed to dissolve all the alum added.

Conclusion: After 3 minutes, all the alum was dissolved. Considering that it is harder to dissolve big quantity of alum, even in big quantity of water, we recommend well stirring the solution during at least 5min after adding alum powder in the water. Check after 5min of stirring if the alum is totally dissolved in the water.

Appendix 7: CAUSTIC SODA, QUANTITIES:

1) Quantity of caustic soda in the mix

The quantity of caustic soda is determined according to (16) and (15):
Hypothesis:

- J. DAVIDOVITS recommends (16) adding caustic soda in order to have a ratio between $0.2 \leq \frac{Na_2O}{Al_2O_3} \leq 0.8$ where Al_2O_3 is the one contained is the kaolin clay. To have a high average of this ratio (according to (16) increasing the amount of caustic soda, the compressive strength increase as well), we chose a ratio $\frac{Na_2O}{Al_2O_3} = 0.6$.
- According to the results of sedimentation tests done 1 month before, we concluded that red soil has approximately 3% of clay. This value seems to be not trustable, but the explanation does not change
- While we do not know the type of clay in the soil, we consider that it is kaolin clay (ratio $c_r = \frac{SiO_2}{Al_2O_3} = 2$).
- $M_{Kaolin\ clay} = c_r * M_{SiO2} + M_{Al2O3}$ (M: Molar mass)

Calculations:

- *mass for the mix needed (m_{cs}):*

$$m_{cs} = \frac{r_{Na2O/Al2O3} \ * \ \%_{clay} * M_{Na2O} * V_{soil} * \rho_{cs}}{100 * M_{Kaolin\ clay}}$$

$r_{Na2O/Al2O3}$: ratio=0.5
$\%_{clay}$: percentage of clay in the soil
M_{Na2O}: molar mass of Na_2O (g/mol)
V_{soil}: volume of soil into the mix (L)
$M_{Kaolin\ clay}$: molar mass of kaolin clay (g/mol)
ρ_{cs}: caustic soda bulk density (kg/L)

- *Percentage in the mix is calculated as other additives (refer to part 2.4, p.20)*

2) *Solution concentration ($\%_{caustic\ soda}$):*

$$\%_{caustic\ soda} = \frac{100 * V_{caustic\ soda} * \rho_{caustic\ soda}}{V_{water} * \rho_{water}}$$

V: volume (L)
ρ: bulk density (kg/L)

Appendix 8: GRAVELS AND PEBBLES DENSITIES RESULTS

In the continuity to characterize materials used for this research, tests on big aggregates were done to know their apparent densities and their specific densities. The specific and bulk densities were determined for the 2" and 1" aggregates[11]. Indeed, others aggregates were already tested with the same method.

sample	dry mass: bulk density (kg)			dry mass: specific density (kg)	recipient mass (kg)			mass in water (kg)	specific density (kg/L)	bulk density (g/L)			
	1	2	3		1	2	3			1	2	3	average
1"	16.914	16.210	16.444	7.802	0.576	0.612	0.580	15.728	**2.264**	1.552	1.487	1.507	**1.51**
2"	15.366	14.912	15.520	9.562	0.572	0.614	0.590	16.710	**2.263**	1.405	1.363	1.420	**1.40**

Table 11: Experimental data on densities measurement

Specific densities are given with 0.005kg/L accuracy while bulk densities with 0.07kg/L accuracy.

Observations:

- Specific density results are approximately the same for both aggregates sizes. This is a good point to confirm the protocol used. Indeed, both aggregates are made from the same stone.
- Otherwise, the bulk density is obviously different because the thinner aggregates are, the more they can fill any space. That means thinner aggregates are organized with a more important compactedness.

[11] Aggregates were not dried in an oven, because we considered them dried enough (under the sun) considering that the used balance was just about a precision of 2g.
Recipient was not shook considering that the aggregate size was big enough to avoid big bubbles.
2'' aggregates have a large dispersal (from 1'' to 4''), and they also have a lot of different shapes.

Appendix 9: RECAPITULATIVE TABLE

series	code	soil	gravels and pebbles	cement	lime	Other additives (coconut fibers, alum, caustic soda)	Water
Control samples	40A_9C_0L	Red: 40%	½": 13% 1": 32% 2": 16%	9%	0%	0%	12%
	50A_9C_0L	Red: 50%	1": 32% 2": 16%	9%	0%	0%	14%
	40A_2M_9C_0L	Red: 20% Mangalam: 18%	½": 13% 1": 32% 2": 17%	9%	0%	0%	15%
	40A_4M_9C_0L	Red: 30% Mangalam: 9%	½": 13% 1": 32% 2": 16%	9%	0%	0%	12%
Cement + Lime	40A_9C_1L	Red: 40%	½": 13% 1": 32% 2": 16%	9%	1%	0%	12%
	40A_9C_3L	Red: 40%	½": 13% 1": 32% 2": 16%	9%	3%	0%	12%
	40A_9C_5L	Red: 40%	½": 13% 1": 32% 2": 16%	9%	5%	0%	13%
	50A_9C_1L	Red: 50%	1": 32% 2": 16%	9%	1%	0%	13%
	50A_9C_3L	Red: 50%	1": 32% 2": 16%	9%	3%	0%	14%
	50A_9C_5L	Red: 50%	1": 32% 2": 16%	9%	5%	0%	15%
Red soil + Mangalam soil	40A_2M_9C_1L	Red: 20% Mangalam: 18%	½": 13% 1": 32% 2": 17%	9%	1%	0%	14%
	40A_2M_9C_3L	Red: 20% Mangalam: 18%	½": 13% 1": 32% 2": 17%	9%	3%	0%	14%
	40A_2M_9C_5L	Red: 20% Mangalam: 18%	½": 13% 1": 32% 2": 17%	9%	5%	0%	15%
	40A_4M_9C_1L	Red: 30% Mangalam: 9%	½": 13% 1": 32% 2": 16%	9%	1%	0%	13%
	40A_4M_9C_3L	Red: 30% Mangalam: 9%	½": 13% 1": 32% 2": 16%	9%	3%	0%	13%
	40A_4M_9C_5L	Red: 30% Mangalam: 9%	½": 13% 1": 32% 2": 16%	9%	5%	0%	13%
Coconut fibers	50A_9C_0L_2F	Red: 50%	1": 32% 2": 16%	9%	1%	Fibers: 0.04%	13%
	50A_9C_0L_4F	Red: 50%	1": 32% 2": 16%	9%	3%	Fibers: 0.08%	13%
	50A_9C_0L_8F	Red: 50%	1": 32% 2": 16%	9%	5%	Fibers: 0.16%	14%

HOMLA	40A_9C_0L_H	Red: 40%	½": 13% 1": 32% 2": 16%	9%	0.01%	Alum: 0.002%	12%
	50A_9C_0L_H	Red: 50%	1": 32% 2": 16%	9%	0.01%	Alum: 0.002%	13%
LAP	40A_9C_1L_P	Red: 40%	½": 13% 1": 32% 2": 16%	9%	1%	Alum: 2.0%	17%
	40A_9C_3L_P	Red: 40%	½": 13% 1": 32% 2": 16%	9%	3%	Alum: 2.6%	21%
	40A_9C_5L_P	Red: 40%	½": 13% 1": 32% 2": 16%	9%	5%	Alum: 2.8%	22%
	50A_9C_1L_P	Red: 50%	1": 32% 2": 16%	9%	1%	Alum: 2.4%	20%
	50A_9C_3L_P	Red: 50%	1": 32% 2": 16%	9%	3%	Alum: 2.7%	22%
	50A_9C_5L_P	Red: 50%	1": 32% 2": 16%	9%	5%	Alum: 2.9%	23%
Geo-polymers	40A_9C_0L_S	Red: 40%	½": 13% 1": 32% 2": 16%	9%	0%	Caustic soda: 0.15%	13%
	40A_0C_3L_S	Red: 40%	½": 13% 1": 32% 2": 16%	0%	3%	Caustic soda: 0.15%	12%
	40A_9C_3L_S	Red: 40%	½": 13% 1": 32% 2": 16%	9%	3%	Caustic soda: 0.15%	14%
	40A_0C_0L_S	Red: 40%	½": 13% 1": 32% 2": 16%	0%	0%	Caustic soda: 0.15%	8%
Earth	40A	Red: 40%	½": 13% 1": 32% 2": 16%	0%	0%	0%	8%
Walls	40A_9C_0L	Red: 41%	½": 11% 1": 31% 2": 17%	9%	0%	0%	15%
	40A_2M_9C_3L	Red: 25% Mangalam: 16%	½": 11% 1": 31% 2": 17%	9%	3%	0%	16%

Table 12: Full recapitulative table of mixes done

Nomenclature:

- 50A: mix with 50% of soil (if M not written, soil is the red soil only)
- 2M: mix with Mangalam soil as ½ of the soil used
- 9C: mix with 9% of Cement
- 3L: mix with 3% of Lime
- 2F: mix with 2 litres of coconut fibers
- H: mix with HOMLA water used instead of tap water
- P: mix with LAP
- W: mix used for walls
- S: mix with caustic soda solution used instead of tap water

Appendix 10: VOLUMES AND PERCENTAGES OF DESIGNED AGGREGATES MIXES

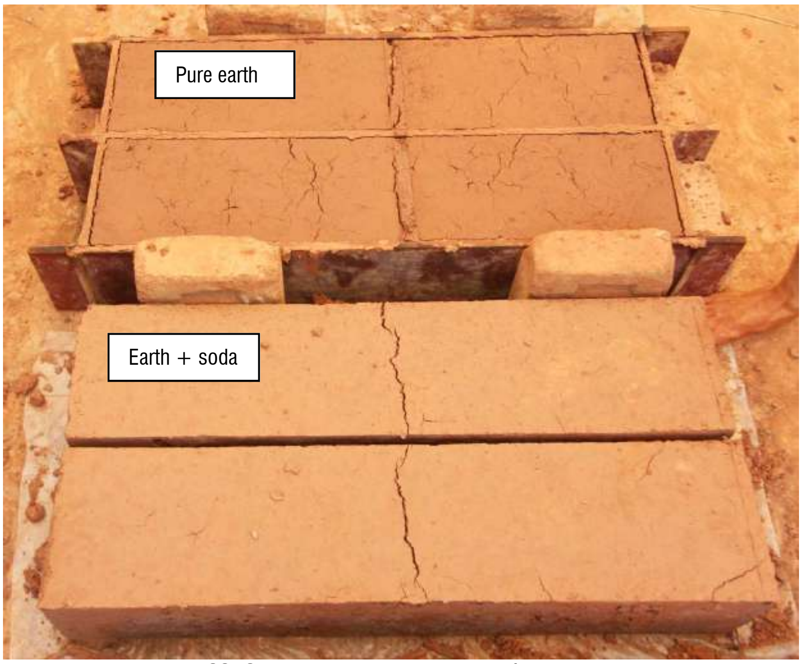
Mix number	Aggregate	REDSOIL	1/2"	1"	2"	Specific density (kg/L)
1	Volume (L)	5	0	1,5	3,5	2,536
	Measured percentage (%mass)	*51,58*	*0*	*14,95*	*33,47*	
2	Volume (L)	5	0	2	3	2,505
	Measured percentage (%mass)	*51,48*	*0*	*20,57*	*27,95*	
3	Volume (L)	5	0	2,5	2,5	2,556
	Measured percentage (%mass)	*51,03*	*0*	*25,49*	*23,48*	
4	Volume (L)	5	0	3	2	2,491
	Measured percentage (%mass)	*50,25*	*0*	*31,03*	*18,72*	
5	Volume (L)	5	0,5	1,5	3	2,51
	Measured percentage (%mass)	*51,1*	*4,88*	*15,43*	*28,59*	
6	Volume (L)	5	0,5	2	2,5	2,474
	Measured percentage (%mass)	*51,34*	*5,58*	*21,88*	*21,2*	

Table 13: Specific densities measured on 6 different aggregates ratios (50% soil)

Mix number	Aggregate	REDSOIL	1/2"	1"	2"	Specific density (kg/L)
1	Volume (L)	4	1	3	2	2,669
	Measured percentage (%mass)	*41,21*	*10*	*31,36*	*17,41*	
2	Volume (L)	4	0,5	3,5	2	2,648
	Measured percentage (%mass)	*41,77*	*5,17*	*36,68*	*16,38*	
3	Volume (L)	4	1,5	2,5	2	2,627
	Measured percentage (%mass)	*41,41*	*15,6*	*25,8*	*17,17*	
4	Volume (L)	4	0,5	2,5	3	2,509
	Measured percentage (%mass)	*42,85*	*5,13*	*25,78*	*26,24*	
5	Volume (L)	4	1,5	3	1,5	2,552
	Measured percentage (%mass)	*39,76*	*14,9*	*30,97*	*14,34*	
6	Volume (L)	4	2	2	2	2,546
	Measured percentage (%mass)	*40,98*	*19,8*	*20,38*	*18,87*	

Table 14: Specific densities measured on 6 different aggregates ratios (40% soil)

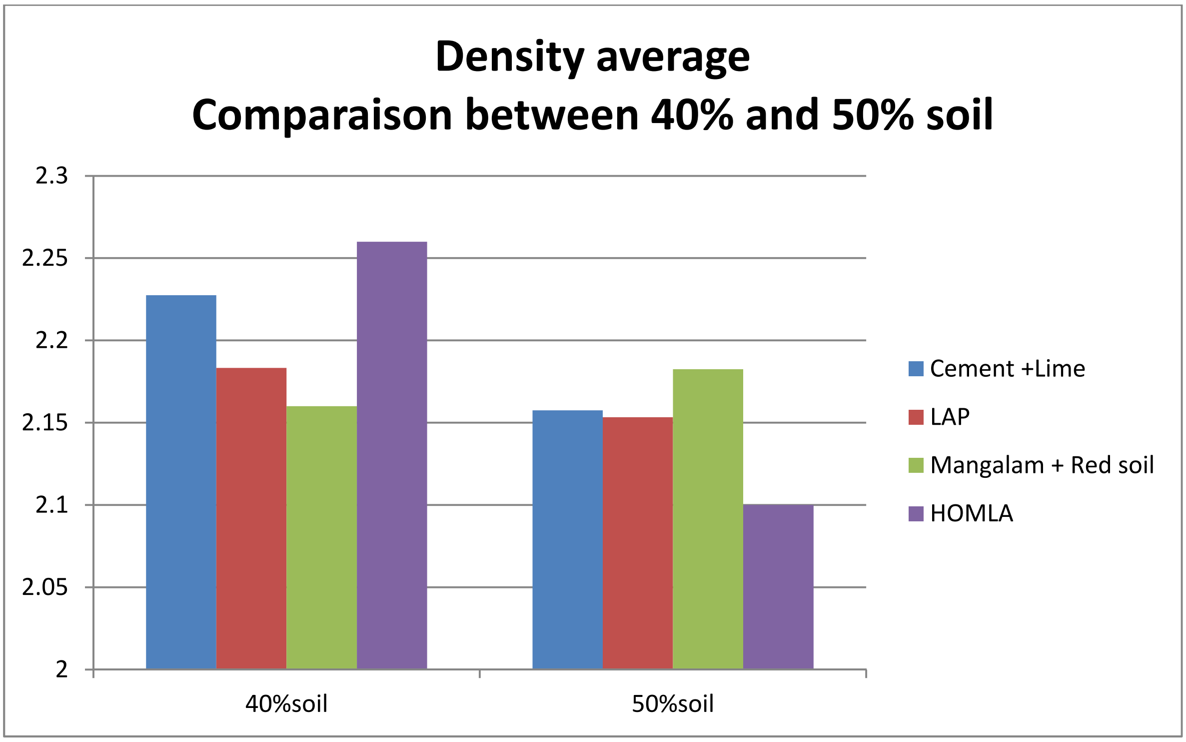
Appendix 11: VISUAL OBSERVATION ON BEAMS WITH AND WITHOUT SODA



Picture 22: Cracks visualization after ~1 week of drying

For these two mixes, all proportions are the same but in mix “earth+soda”, 0.15% (of the dry mix) of soda was added in the water. Samples poured with pure earth (with usual quantities of gravels and pebbles added) show more cracks than samples poured with additional soda.

Appendix 12: COMPARISON GRAPH FOR DENSITIES



Graph 46: Comparison graph for densities, between 40%soil and 50%soil. t