INSA de Lyon - 5GCU
Civil Engineering and Town Planning department

Placement tutor : Gislain LIPEME-KOUYI
Supervisor : Satprem MAINI

INTERNSHIP REPORT

Research and Development Project : Poured Earth

Jérôme COCHET

Auroville Earth Institute, July-September 2011

Summary

The following report sums up my work at the Auroville Earth Institute, as a researcher on the problematic of Poured Earth. This internship occurred between July and October 2011, when I joined AVEI to go further with some research which had already been made by a previous intern, Alberic Le Huede. During these 10 weeks of work, I mainly tried to conciliate the soil mechanics approach which is developed at the institute with what I would call a "concrete approach", i.e. bringing the knowledge I have about concrete construction, being myself a civil engineer. The problematic of my studies was to design poured earth mixes which would provide the best results in term of compressive strength, shrinkage and workability, those parameters being closely related by the water added.

The first tests where performed on the aggregates used to design poured earth mixes: I conducted simple tests on a whole range of mixes, so as to find out what ratios would give the best results in term of bulk ratio (compacity of the mix). Complete sieve analyzes performed on all kind of raw materials that are being used in Auroville (soil, sand, gravels...) were the second part of my research. Using a classical method for the formulation of concrete mixes, I tried to evaluate whether it could also be applied to poured earth.

To go further with these studies and try to optimize the mixes, I realized an important range of samples, both cylinders and cubes, which could be tested under compressive tests at different times after the day of pouring. According to the results I obtained, I designed some additional samples, slightly changing some parameters such as the amounts of sand and soil, of fine particles, or using another binder (cement, lime and plaster of Paris were tried)... I could finally choose three optimum mixes out of all the ones I had made, and use them to design 1:1 walls. This three 120*225*24 cm walls where realized in the middle of my internship, and we could analyze their shrinkage together with the development of cracks in the structure.

In the final part of my internship, I focused on soil analyzes, since I realized no real lab tests were performed at AVEI, often replaced by simple sensitive tests. Therefore I decided to run my own lab tests on the local soil, in order to compare the results with sensitive knowledge, and try to be more accurate in the characterization.

Acknowledgement

Many thanks to all people working at the Auroville Earth Institute, mainly to Satprem Maini, supervisor of this internship, for welcoming me in Auroville in their premises during these ten weeks of internship.

Thanks to the National Institute for Applied Sciences in Lyon, its Civil Engineering department and Gislain Lipeme-Kouyi, my internship tutor.

Thanks to T.Ayyappan for helping me in all of my research, and being always here to answer my requests.

Thanks to CRATerre and MATEIS lab, especially to Magali Aupicon, Sandrine Maximilien and Lionel Ronsoux who nicely answered my questions and gave me some precious help and documentation.

A deep thank to Explora Sup in according me a precious grant which allowed me to attend this internship, and spend some time in this amazing country.

Warm thanks to all the volunteers of the Institute and their constant cheerful mood.

Many thanks to Mr. Michael Frerking, who accepted to share with us his precious works on poured earth. He will be a precious research partner in the future.

Finally, many thanks to Satprem Maini, Vanessa Porret, Gislain Lipeme-Kouyi and Jean-Luc Bertrand-Krajewski for being so comprehensive about my complicated situation this summer, and accepting to shorten the duration of my internship.

Contents

1 Designing dry agreggate mixes **13**
- 1.1 Objective . . . 13
- 1.2 Principle of the test . . . 13
  - 1.2.1 Apparent density . . . 13
  - 1.2.2 Specific density . . . 13
  - 1.2.3 Designing the tests . . . 14
  - 1.2.4 Results and conclusions for the six mixes . . . 15
  - 1.2.5 Designing a second range of tests . . . 16
  - 1.2.6 Results . . . 16
  - 1.2.7 Conclusions . . . 17
- 1.3 Conclusion of dry tests . . . 18

2 Sieve analyses **19**
- 2.1 Objective . . . 19
- 2.2 Principle of the tests . . . 19
- 2.3 Results . . . 20
  - 2.3.1 Soil . . . 20
  - 2.3.2 Sand . . . 21
  - 2.3.3 Gravels . . . 22
  - 2.3.4 Granite Dust . . . 22
- 2.4 Conclusions . . . 23

3 Designing a Tool for Formulation
Applications: samples and walls. **25**
- 3.1 Objective . . . 25
- 3.2 Principle and How To Use the Tool . . . 25
- 3.3 About the method : conclusions . . . 28

4 Compressive tests **30**
- 4.1 Objective . . . 30
- 4.2 Samples design . . . 30

4.3 Procedure for making of samples . . . 31
4.4 Water content of the mixes . . . 32
4.5 Estimation of the density . . . 33
4.6 Compressive strength . . . 35
4.6.1 Failure modes . . . 35
4.6.2 The case of lime . . . 35
4.6.3 Results on cylinders . . . 36
4.6.4 Results on cubes . . . 37
4.6.5 Comparison between cubes and cylinders . . . 38
4.7 Estimation of the Young's Modulus . . . 39
4.7.1 Tests on poured earth . . . 39
4.7.2 Tests on steel . . . 40
4.7.3 Conclusions about Young's Modulus . . . 43

5 The walls 44
5.1 Introduction and objective . . . 44
5.2 Procedure for pouring a wall[1] . . . 45
5.3 Results and comments . . . 45
5.3.1 General comments . . . 45
5.3.2 About water . . . 46
5.3.3 Final densities . . . 46
5.3.4 Conclusion . . . 47

6 Additional samples 48
6.1 Objective . . . 48
6.2 New leads for poured earth mixes . . . 48
6.2.1 Plaster of Paris (P.O.P.) . . . 48
6.2.2 Crushed firebricks . . . 49
6.2.3 Lime + Cement . . . 49
6.2.4 Chemicals and additives . . . 49

7 Conclusion 51

8 Next steps 53

Appendices 55
.1 Introduction . . . 56
.2 Appendix to Chapter 2 . . . 57
.2.1 Procedure for sieve analyes(cf. Fig. 1) . . . 57
.2.2 Sample calculation sheet . . . 58

[1] Please refer to Appendix .5, p. 70 for all the correponding pictures.

.2.3 Gradation curves for all materials 58
.3 Appendix to Chapter 3 63
.3.1 Dreux and Gorisse method: ideal gradation areas for concrete mixes, D<20mm and D<40mm 63
.3.2 Views of the tool interface 64
.4 Appendix to Chapter 4 65
.4.1 Procedure for making samples 65
.4.2 Close-ups on the different samples (series with cement) 67
.4.3 Tests under compressive strength : cylinders and cubes 68
.4.4 Young's modulus : data collection 69
.5 Appendix to Chapter 5 70
.5.1 Procedure for making walls 70

9 Bibliography **72**
9.1 Books & Publications 72
9.2 Main Websites 72

List of Figures

1.1 Handling for measuring specific density 14
1.2 Composition of the six mixes designed 15
1.3 Measuring apparent density 15
1.4 Measuring specific density 15
1.5 Results for the six mixes in term of compacity 16
1.6 Design for the second range of tests 16
1.7 Results for gravels in term of compacity 17
1.8 Results for soil and sand in term of compacity 17

2.1 Sieve shaker used for sieve analyses 20
2.2 Soil gradation 20
2.3 Gradation curves for soil 21
2.4 Gradation curves for sand 21
2.5 Gradation curves for gravels 22
2.6 Gravel chips gradation 22
2.7 Half inch Gravel gradation 22
2.8 Half inch Gravel gradation 24

3.1 Data board (results obtained thanks to gradation tests) 26
3.2 Average values, obtained thanks to the data board 26
3.3 User interface, the ratios should be entered in the white cells . 26
3.4 Gradation curves obtained for each one of the six mixes previously designed 27
3.5 Design for the walls 27
3.6 Design for the walls 28

4.1 1st range of samples : 1Cy and 1C series 30
4.2 The six different dry agreggate mixes used for designing samples 31
4.3 Water contents for S1, S2 and S3 Slump classes 32
4.4 Water contents for S2 and S3 Slump classes 32
4.5 Water contents for S1, S2 and S3 Slump classes 33

4.6 Water contents for S2 and S3 Slump classes 33
4.7 Values of density measured on cylindrical samples 34
4.8 Values of density measured on cubic samples 34
4.9 Illustration of the friability of the samples made using lime . . 36
4.10 Compressive strength obtained on cylinders 36
4.11 Variations of strength with curing time and quantity of cement 37
4.12 Compressive strength obtained on cubes 38
4.13 Results on cubes and cylinders 39
4.14 Example of strain-stress curve for a cube 40
4.15 Strain-stress for a 50x50x50 cube of steel 42
4.16 Strain-stress for a 50x50x50 cube of steel : linear area 42

5.1 The three different dry agreggate mixes used for designing walls 44
5.2 The three walls after unmolding and 28 days curing 45
5.3 Quantity of water used for the walls 46
5.4 Expansion rates for the walls 46

1 Sieve analyses 57
2 1st range of samples : 1Cy and 1C series 58
3 Soil 0 58
4 Soil 1 59
5 Soil 2 59
6 Sand 1 59
7 Sand 2 60
8 Gravel Chips 1 60
9 Gravel Chips 2 60
10 Half Inch Gravels 1 61
11 Half Inch Gravels 2 61
12 Granite Dust 1 61
13 Granite Dust 2 62
14 D<20mm, ideal area located as "Fuseau de référence" 63
15 D<40mm, ideal area located as "Fuseau de référence" 63
16 Interface 64
17 Interface 64
18 Sample making (1) 65
19 Sample making (2) 66
20 Series 1CCy 67
21 Example of shear failure on cylinder 68
22 Example of cone failure on cylinder 68
23 Failure on cube 68
24 Data collection on multiple photographs 69

25 Close-up on strain and stress screens 69
26 Building walls (1) 70
27 Building walls (2) 71

Introduction

From traditional earthen architecture to CSEB

Earth has been employed for construction for thousands of years, in all parts of the world. It is a local and cheap material, which can be found everywhere, although its quality and composition may vary from one place to another. Today 40% of the world population lives in an earth house. Many different techniques exist worldwide, allowing building a various range of housing, from small shelters to several-stories structures.

However, with the improvement of many others building techniques such as stone, firebrick, wood or concrete, earthen construction remained only a traditional way of building, and suffered from a lack of interest from the scientific community, since no real research was carried out for decades.

But since the 50's, earthen architecture has known a renewed interest, and an important number of laboratories all over the world are constantly improving the existing techniques in order to develop greener and cheaper ways of living. Among them we can quote CRATerre, the International Centre for Earth construction which is based in France and is one of the world leaders since 1975, and the Auroville Earth Institute based in India, where I interned.

Inspired by different traditional earthen techniques of building, compressed stabilized earth blocks (or CSEB) are a modern technology nowadays used in various parts of the world. It consists in the compression of a mix of soil and sand, previously stabilized to guaranty its resistance to water. Common stabilizers are cement and lime, employed according to the nature of the local soil. Many studies have been conducted to determine the optimal ratios of all the components, along with the pressure applied to the block, its dimensions and conditions of conservation, all of these parameters depending on the characterization of the soil. A lot of studies have been conducted here at AVEI, bringing CSEB technology from an experimental scale to a constructive reality.

Indeed many buildings in Auroville are examples of CSEB architecture, which allows to build several stories, walls and roofing included when used along with vaults, domes and arches techniques.

Learning from concrete construction

Alongside research conducted on earth, the XX^{th} century has witnessed the expansion of concrete, which increasingly developed all over the world in a few decades, and is now the first materials used in construction. Its strength, workability and compatibility with steel is an answer to most of architectural designs.

Poured Earth is a technology which would conciliate the characteristics of concrete with the employment of local aggregates. The product would use less cement than a traditional concrete, providing a resistance strength determined by its intended use. Addition of water to the aggregates would allow to get a workable (plastic to liquid) mix which could be poured in frameworks as concrete, allowing manufacturing of walls, beams, slabs... A possible compatibility with steel would open the way to reinforced poured earth...

There are many other interests in poured earth technology: as its mechanical and chemical behavior would be close to concrete, the full range of already existing machines could be used. Testing processes and calculation methods could also be strongly inspired by those developed for concrete technology, enabling constructors to easily employ it.

Since poured earth can directly be implemented on site in its final shapes, it would no longer be necessary to have pre-production sites such as for CSEB. The labor would be reduced with the costs, and the construction cadency increased.

An introduction to poured earth research

For all these reasons, it is understood that poured earth is a strongly promising technology, which nowadays only exists at an experimental level. Therefore it is fundamental to implement research projects, and develop on-site experimentations in the years to come.

I wanted to study poured earth in terms of a new concrete technology, therefore employing the classical methods and norms inherent to concrete

buildings. Workability tests, sieve analyzes, making of samples or construction of walls were strongly influenced by concrete knowledge: thus I could experiment the behavior of poured earth, see its common points with concrete, and understand some of their differences to design optimal mixes.

The following pages are a summary of my research work, presenting the results I obtained, conclusions which can be drawn, and new leads to follow...

Chapter 1

Designing dry agreggate mixes

1.1 Objective

The objective of this test is to get a first overview of the different material ratios which will then be employed to realize the first series of samples. We aim to find the best dry aggregate ratio, i.e. the dry mix which will reach the maximum of compacity.

1.2 Principle of the test

The compacity of a dry mix of different materials is defined as its apparent density (kg/L) divided by its specific density (kg/L) :

$$C = \frac{\rho_{app}}{\rho_{sp}} \tag{1.1}$$

1.2.1 Apparent density

The apparent density, or bulk density is defined as the ratio between the weight of the dry specimen and its apparent volume; i.e. the volume limited by the external surface of the specimen including any voids. To determine the apparent density of an aggregate mix, we weight first the mass of the sample in a cylindrical recipient. By properly leveling the surface of the mix, we can get its apparent volume.

1.2.2 Specific density

The specific density of a material is the weight of a given quantity of the material divided by the sum of the volumes of the particles contained in the

same quantity.

$$\rho_{spec} = \frac{P_1 \rho'}{P_0 + P_1 - P_2} \tag{1.2}$$

Where P_0, P_1, P_2 as shown on Figure 1.1, $\rho' = 1$ being the density of water.

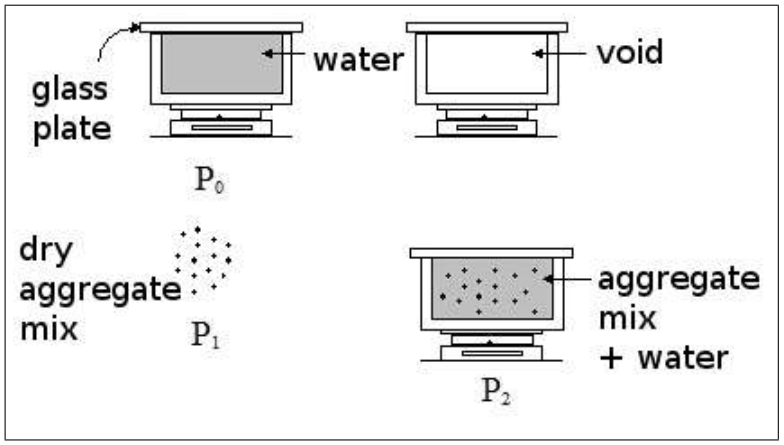


Figure 1.1: Handling for measuring specific density

Principle

- Fill the recipient with water and cover it with the glass plate to make sure that no air remains between glass and water. Weigh all. Then remove water from the recipient.
- Weigh a mass P1 of dry mix ;
- Put the mix of weight P1 in the recipient, and then fill it with water, making sure there is no air remaining by stirring the mix. Complete filling as before ;
- Weigh everything: P2.

1.2.3 Designing the tests

The test will be done with several mixes, as described below. The different ratios between soil, sand and gravel should give a sufficient range to get a

first idea about the best dry aggregate mix. We will then pour real samples and test them under compression to compare the results.

	MIX 1	MIX 2	MIX 3	MIX 4	MIX 5	MIX 6	1/2" GRAVEL	GRAVEL CHIPS	SAND	SOIL
Soil	40%	30%	25%	20%	15%	10%	0%	0%	0%	100%
Sand	40%	30%	25%	20%	25%	20%	0%	0%	100%	0%
Gravel Chips	10%	20%	25%	30%	20%	30%	0%	100%	0%	0%
1/2" Gravel	10%	20%	25%	30%	40%	40%	100%	0%	0%	0%

Figure 1.2: Composition of the six mixes designed

Once the mixes are ready (made by hand, weighing the different masses of materials), we first determine their apparent density, then their specific density. Finally, we can easily calculate their compacity and compare the different results.

Figure 1.3: Measuring apparent density

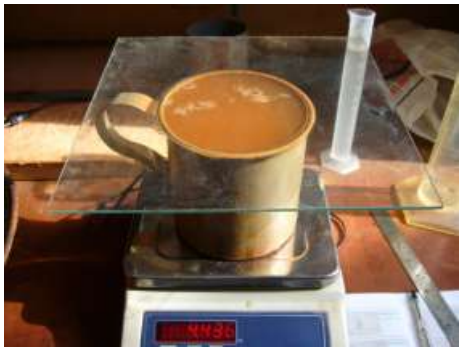
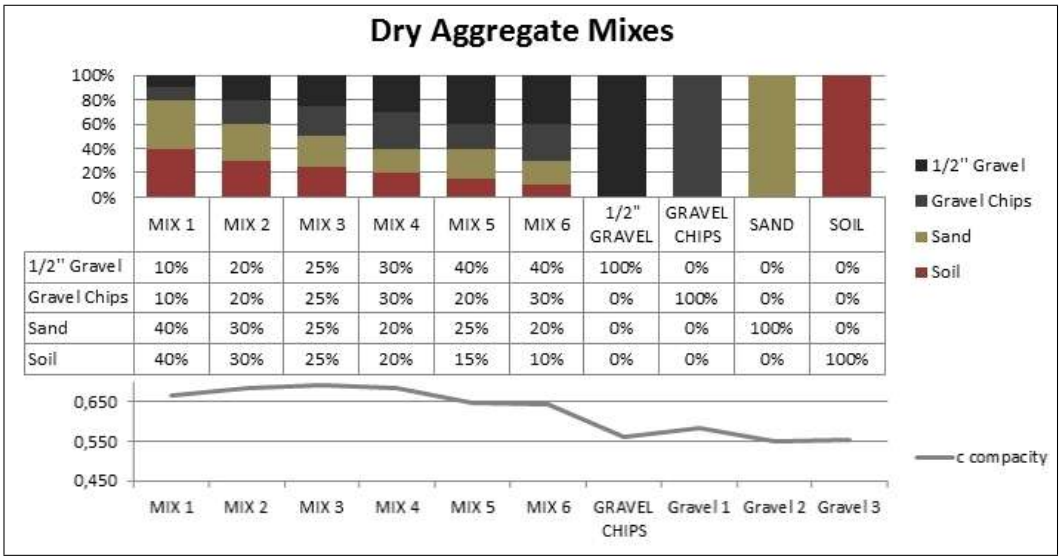


Figure 1.4: Measuring specific density

1.2.4 Results and conclusions for the six mixes

From this first range of experiments we can infer that the best ratio between the different components of the dry aggregate mix seems to be reached for the 3rd mix, which includes 50% Gravel (25% half inch Gravels and 25% Gravel Chips), 25% Soil and 25% Sand. We then decided to improve these results by launching a second series of tests. We will now work separately on both ratios half inch Gravels / Gravel Chips and Soil / Sand. Since the soil we use contains an undefined fraction of sand, it seems interesting to focus on the mix sand-soil, and find its best ratio.



	MIX 1	MIX 2	MIX 3	MIX 4	MIX 5	MIX 6	1/2" GRAVEL	GRAVEL CHIPS	SAND	SOIL
1/2" Gravel	10%	20%	25%	30%	40%	40%	100%	0%	0%	0%
Gravel Chips	10%	20%	25%	30%	20%	30%	0%	100%	0%	0%
Sand	40%	30%	25%	20%	25%	20%	0%	0%	100%	0%
Soil	40%	30%	25%	20%	15%	10%	0%	0%	0%	100%

Figure 1.5: Results for the six mixes in term of compacity

1.2.5 Designing a second range of tests

We are now separately trying to estimate the ratios of Gravels and Soil/Sand which will give us the best compacity when mixed. Therefore we will design the samples with different ratios of aggregates, as it appears on figure 1.6.

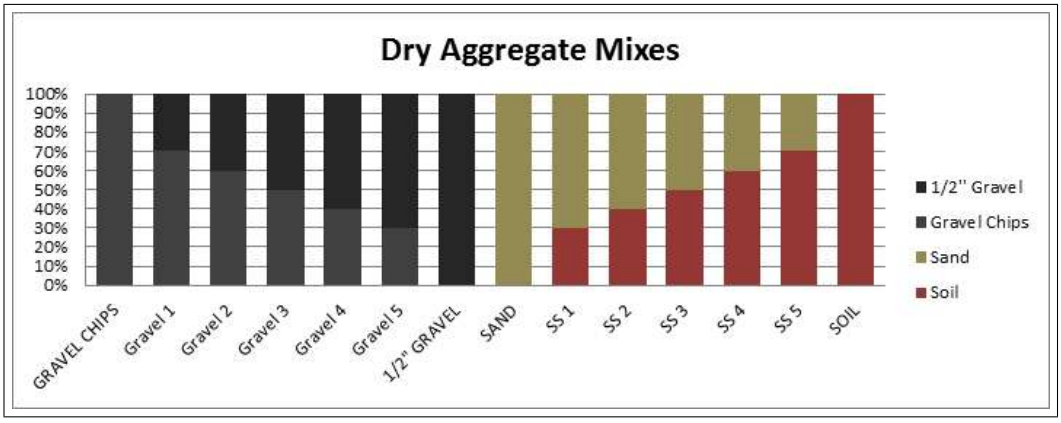


Figure 1.6: Design for the second range of tests

1.2.6 Results

We can first focus on the gravel mixes and analyze the results provided by the tests we run. We notice that the curve compacity f(ratio) doesn't seem to

follow a simple tendency : there is no maximum point, so it's impossible to infer from the test an ideal ratio between our two kinds of gravels. Perhaps the protocol of experimentation isn't precise enough for gravel mixes. It would be good to run the tests again using a bigger recipient, which should give better results.

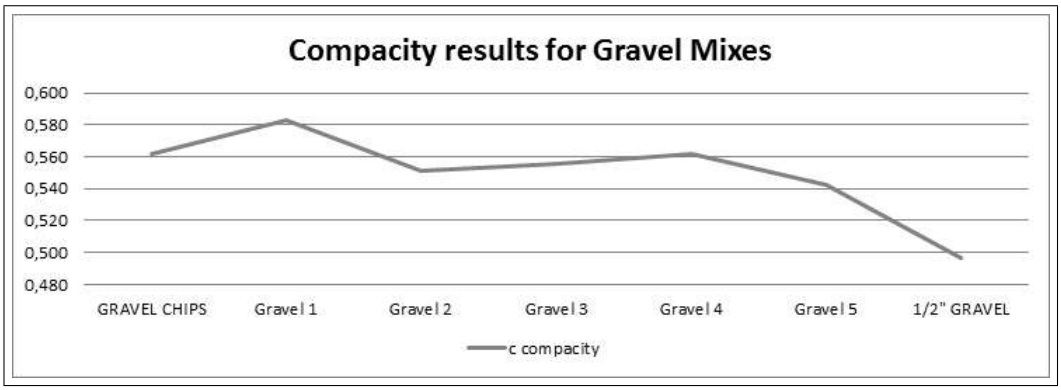


Figure 1.7: Results for gravels in term of compacity

Concerning the soil/sand mixes, the results are much more useful : there is a maximum point, located between the mixes SS2 and SS4. Out of the range of tests done here, the mix SS3 (50% Sand / 50% Soil) gives the best result, with a compacity of 0,697.

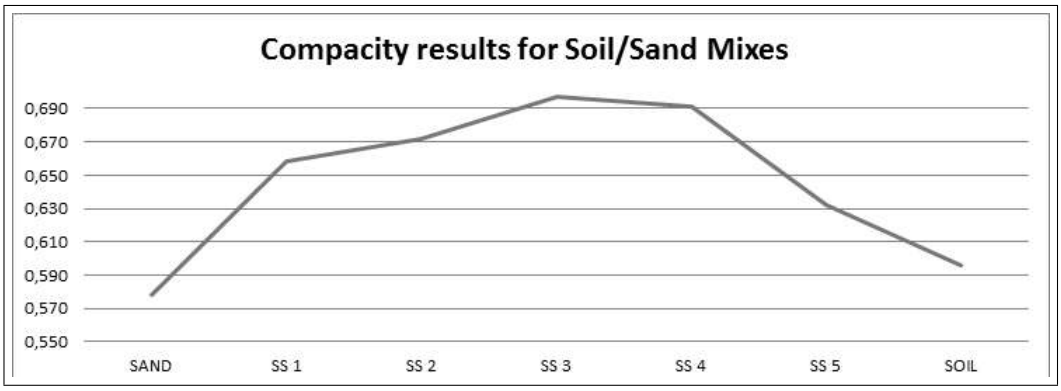


Figure 1.8: Results for soil and sand in term of compacity

1.2.7 Conclusions

From this second range of tests, we can't infer any ideal ratio between half inch gravels and gravel chips. Some new tests should be run to know more

about the best mix of gravels. On the other hand, we can say that a 50/50 ratio between soil and sand gives a very good compacity.

1.3 Conclusion of dry tests

The different results obtained through these first series of tests seem to be coherent and lead to the same conclusions: whereas it's now difficult to guess the best ratio of gravels, we can conclude that using a 50/50 ratio of soil/sand will lead to the best compacity. Also the mix including 25% sand, 25% soil, 25% gravel chips and 25% half inch gravels is the best in term of compacity. We can now pour real samples of the different dry aggregate mixes tested here, which should confirm the present results, and allow us to know more about their resistance under compressive strength.

Chapter 2

Sieve analyses

2.1 Objective

The aim of performing a sieve analyses on the different dry materials that we commonly use at the Auroville Earth Institute is to assess the particle size distribution, or gradation of these granular materials. The results of these tests are a representation of the gradation on "gradation curves", which will be useful for the formulation of concrete, or any kind of mix including several sorts of these materials.

2.2 Principle of the tests

The test is using a sieving machine, in addition with a 10 sieves range, whose mesh dimensions are (in mm) : 20 ; 10 ; 5,6 ; 3 ; 2 ; 0,5 ; 0,425 ; 0,3 ; 0,212 ; 0,106 [1]

1. All sieves are weighed while empty.
2. Sieves are piled up to form a column, from bigger (up) to tinier (bottom) mesh. An additional cup is placed at the bottom.
3. Upper sieve is filled with 1kg of dry material (e.g. soil, sand or gravels), then covered.
4. Sieves are placed on the machine, which will shake the system for approximately 1mn.

[1] NB: there was no information given about three of the sieves, therefore the mesh was approximately deduced by eye and using the modulus written on the sieves. The error made on this estimation should not disturb the results, but it's important to note that we are not performing a 100% rigorous test.

5. Sieves are removed from the machine, then weighed one by one after manually completing the sieving, using a simple brush.

The test was performed twice for all the materials : raw soil, crushed soil, sand and gravels. Soil and sand had been left for 24 hours in the oven before sieving.

Figure 2.1: Sieve shaker used for sieve analyses

2.3 Results

The following paragraphs will sum up the results obtained for the different tests performed. Additional information about calculation procedure can be found in the corresponding .xls sheet. Also the complete series of gradation curves is available in annexes.

2.3.1 Soil

Figure 2.2: Soil gradation

It clearly appears that raw soil left outside for a long period presents a phenomenon of flocculation of its fine particles, probably due to moisture

and variations of weather. Therefore, it is particularly interesting to see if a proper crushing of the soil will consequently modify its gradation. A proper portion of soil was dried in the oven, and then crushed by hand with bricks before running the test.

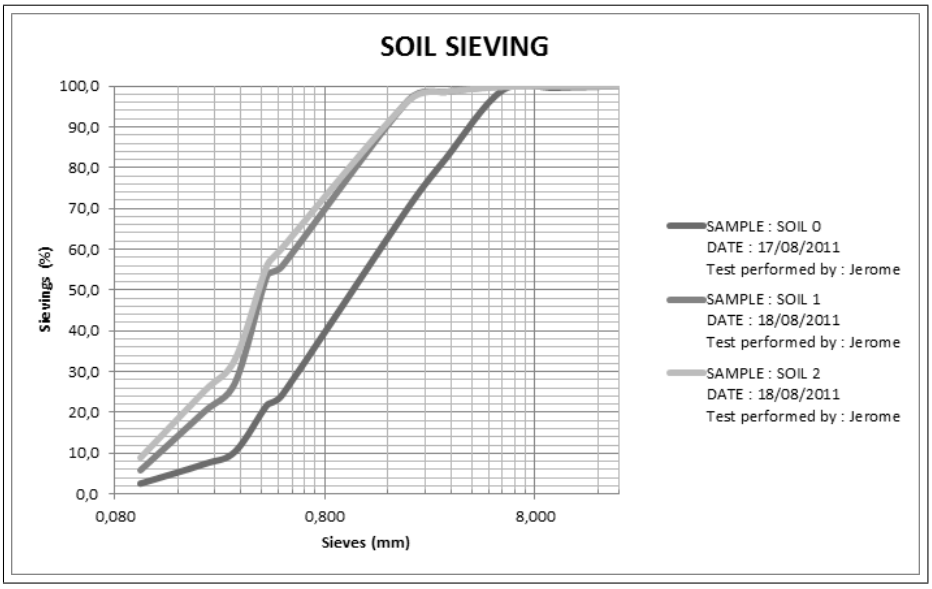


Figure 2.3: Gradation curves for soil

2.3.2 Sand

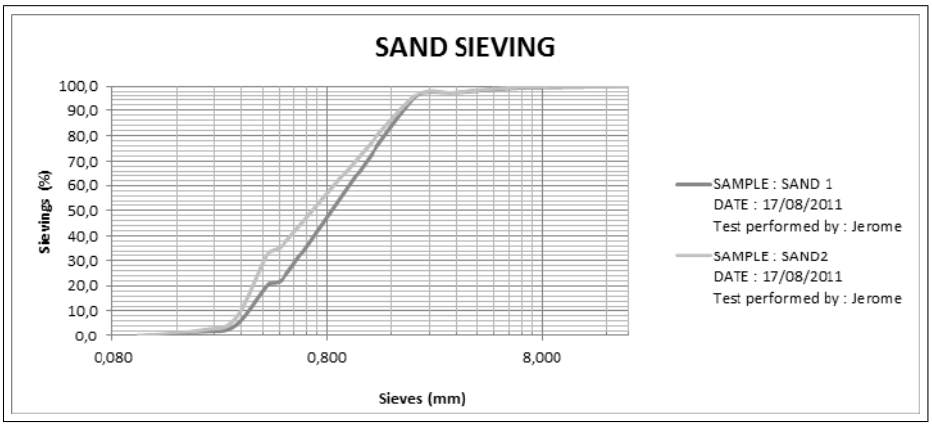


Figure 2.4: Gradation curves for sand

2.3.3 Gravels

Two types of gravels were tested : Gravel chips and Half inch Gravels.

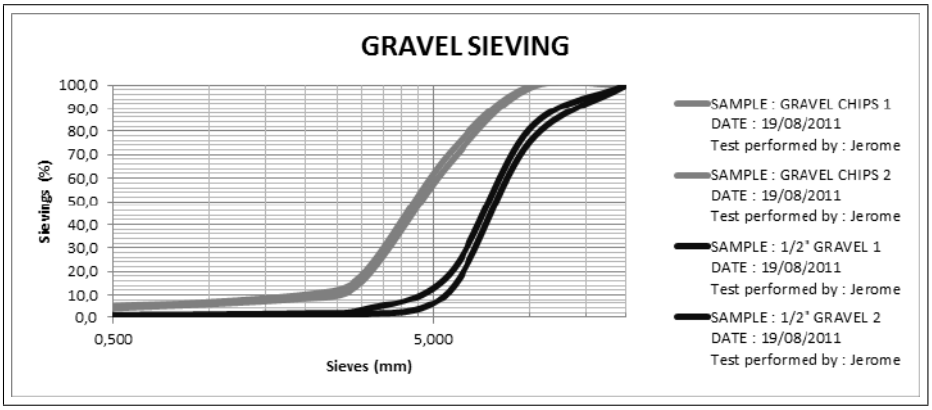


Figure 2.5: Gradation curves for gravels

Figure 2.6: Gravel chips gradation

Figure 2.7: Half inch Gravel gradation

2.3.4 Granite Dust

Finally, I also made some additional tests on granite dust, a material which is obtained throughout the making of gravels out of granite stone. It is easy to get, and quite cheap, therefore it could be an interesting alternative to

sand. Analyzing its gradation will give us a good idea on how and in which proportions it could be included in a poured-earth mix. The gradation curves are in the annex files, and was also added to the figure 2.8 : we see that it contains a lot of fine particles[2], which is not really good for our tests : actually there is already a lot of fine sand, silts and clays in the soil that we use, and adding more to our concrete would give poor resistances and high shrinkage. It seems that it is a way we should forget about.

2.4 Conclusions

There are no real "conclusions" which can be drawn out of these analyses. However, it is fundamental to get knowledge about the materials we are using here for all kinds of purposes. Since these soil, sand and gravels are used a lot at AVEI and even in the whole Auroville, getting to know there gradation can be very useful, particularly as they help formulating aggregate mixes (concrete, blocks, road construction). They also represent a good way to know more about the quality of the sand (is it a good for concrete?), and about the components of the soil (fraction of fine particles = silts and clays). The following graph sums up all the tests performed for this report : average values are used to draw the curves corresponding to each type of material. We are using results for crushed soil rather than "raw" soil.

[2]Note that granite dust is a residue from the grinding of granite stones; these "fine particles" are a fine powder of granite and do not include clay.

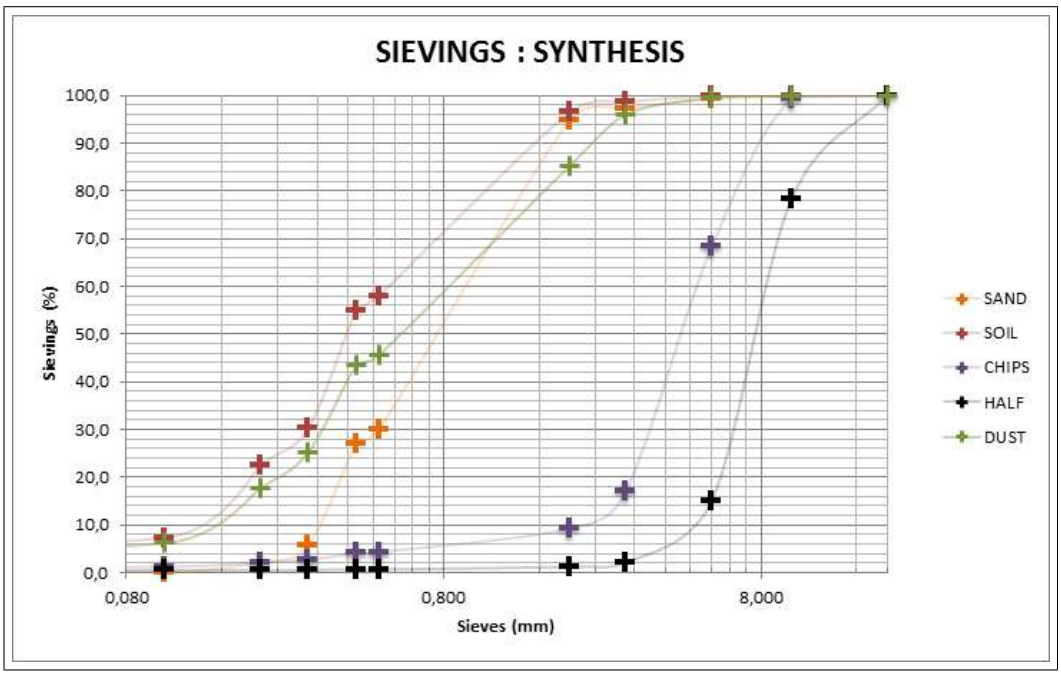


Figure 2.8: Half inch Gravel gradation

Chapter 3

Designing a Tool for Formulation *Applications: samples and walls.*

3.1 Objective

After processing sieve analyses on all the variety of materials that we can find in Auroville and AVEI, I thought it would be interesting to develop a tool which could help designing the poured earth mixes. According to the ratios included, it would give an idea of the final quality of the concrete.

3.2 Principle and How To Use the Tool

Since we don't know much about poured earth, and no real documentation nor databases are available, I chose to base this tool on concrete methods. Indeed, exception made for the soil, the other components are all similar to those used in a traditional concrete mix, and therefore it should provide us a good approximation. The tool is a basic software designed on an excel sheet. The gradation results obtained for each type of material are given first, and average values are calculated to characterize them separately, as we can see on the picture below.

The user can then enter in the appropriate cells the percentages of different components that he wants to mix together: soil, sand, granite dust, gravel chips, half inch gravels and one inch gravels are included. It is of course possible in the future to add new types of materials if necessary. The ratios should be entered out of volume, then the software will automatically calculate the corresponding mass ratios, according to the apparent density, which are already provided for all kinds of aggregates.

As we can see on figure 3.4, the software allows to draw up to 6 curves

Sieve	MESH(mm)	DATA											
		SAND1	SAND2	SOIL0	SOIL1	SOIL2	CHIPS1	CHIPS2	HALF1	HALF2	DUST1	DUST2	ONE
-	20,000	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100
-	10,000	99,7	100,0	99,6	100,0	100,0	99,6	98,8	81,2	75,6	99,8	99,8	0
200	5,600	99,1	99,4	99,0	100,0	99,8	70,6	66,2	18,8	11,5	99,6	99,4	0
170	3,000	97,1	97,4	82,2	98,6	98,6	18,4	13,7	3,2	1,2	95,8	96,2	0
50	2,000	94,3	95,2	70,3	96,6	96,4	10,3	8,3	1,8	0,8	84,7	85,9	0
-	0,500	23,0	36,8	24,2	55,8	60,3	4,7	3,9	1,0	0,4	45,2	45,9	0
30	0,425	20,7	33,4	21,9	53,6	56,1	4,5	3,7	1,0	0,4	43,6	43,3	0
-	0,300	4,5	7,2	10,5	27,5	33,2	3,0	2,6	0,8	0,4	25,1	25,4	0
-	0,212	1,8	2,6	7,3	20,1	25,1	2,4	2,0	0,6	0,4	17,7	17,9	0
-	0,106	0,2	0,2	2,6	3,8	8,9	1,4	1,2	0,6	0,4	6,0	6,4	0
Bottom	0,000	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0

Figure 3.1: Data board (results obtained thanks to gradation tests)

AVERAGE				
SAND	SOIL	CHIPS	DUST	HALF
100,0	100,0	100,0	100,0	100,0
99,8	100,0	99,2	99,8	78,4
99,3	99,9	68,4	99,5	15,2
97,3	98,6	17,0	96,0	2,2
94,8	96,5	9,3	85,3	1,3
29,9	58,0	4,3	45,6	0,7
27,1	54,9	4,1	43,5	0,7
5,9	30,4	2,8	25,3	0,6
2,2	22,6	2,2	17,8	0,5
0,2	7,4	1,3	6,2	0,5
0,0	0,0	0,0	0,0	0,0

Figure 3.2: Average values, obtained thanks to the data board

CURVE 1	Aggregate	SOIL	SAND	DUST	CHIPS	HALF	ONE	TOT
	QUANTITY (%vol)	40	40	0	10	10	0	100
	QUANTITY (%mass)	36,20	44,15	0,00	9,86	9,79	0,00	100
CURVE 2	Aggregate	SOIL	SAND	DUST	CHIPS	HALF	ONE	TOT
	QUANTITY (%vol)	30	30	0	20	20	0	100
	QUANTITY (%mass)	27,27	33,26	0,00	19,81	19,66	0,00	100
CURVE 3	Aggregate	SOIL	SAND	DUST	CHIPS	HALF	ONE	TOT
	QUANTITY (%vol)	25	25	0	25	25	0	100
	QUANTITY (%mass)	22,78	27,78	0,00	24,81	24,63	0,00	100
CURVE 4	Aggregate	SOIL	SAND	DUST	CHIPS	HALF	ONE	TOT
	QUANTITY (%vol)	20	20	0	30	30	0	100
	QUANTITY (%mass)	18,26	22,27	0,00	29,84	29,62	0,00	100
CURVE 5	Aggregate	SOIL	SAND	DUST	CHIPS	HALF	ONE	TOT
	QUANTITY (%vol)	30	30	0	30	10	0	100
	QUANTITY (%mass)	27,25	33,23	0,00	29,69	9,82	0,00	100
CURVE 6	Aggregate	SOIL	SAND	DUST	CHIPS	HALF	ONE	TOT
	QUANTITY (%vol)	10	20	0	30	40	0	100
	QUANTITY (%mass)	9,06	22,11	0,00	29,62	39,20	0,00	100

Figure 3.3: User interface, the ratios should be entered in the white cells

simultaneously, which can be interesting if a comparison between a wide range of mixes is necessary. On the example which is given here, we will draw the curves which correspond to the six different mixes we designed in the first range of cylindrical and cubic samples (series 1Cy and 1C, whose results under compression strength will be easily found in the corresponding report). Then the software will automatically draw the curves that are designed, all together on the same graph, and compare them with an "ideal" area, in which our curve should be located in order to get a good concrete mix, as a

matter of compacity, strength and homogeneity.

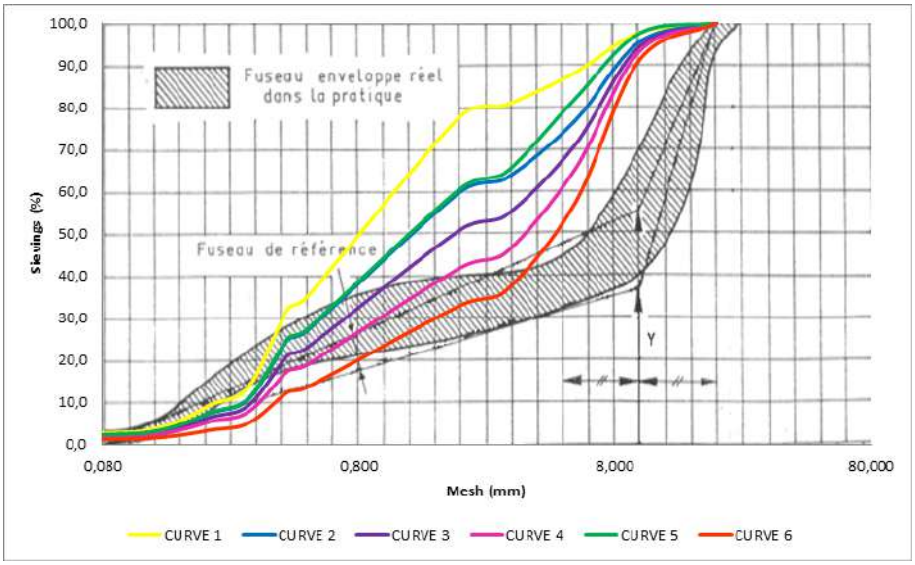


Figure 3.4: Gradation curves obtained for each one of the six mixes previously designed

All of these mixes have been also poured in cylindrical and cubic samples, so as to be able to compare the results after breaking: we should be able to match the location of the curve in or out of the grey area, and the compression strength obtained. Here we observe a lack of big gravels, since we cannot include them in samples. Also it seems that there is always a lack of fine and medium sands, while the fine particles ratio is difficult to evaluate on the only base of dry sievings.

For the making of walls, which was decided later, I tried to adapt these curves with using 1" gravels. The mixes were designed according to the results that we obtained under compressive strength : we chose to keep only the 3rd, 4th and 5th mixes, which were giving the best resistance.

	Aggregate	SOIL	SAND	CHIPS	HALF	ONE	TOT
CURVE 1	QUANTITY (%vol)	25	25	15	15	20	100
	QUANTITY (%mass)	22,79	27,80	14,90	14,79	19,72	100
	Aggregate	SOIL	SAND	CHIPS	HALF	ONE	TOT
CURVE 2	QUANTITY (%vol)	20	20	20	20	20	100
	QUANTITY (%mass)	18,28	22,29	19,91	19,76	19,76	100
	Aggregate	SOIL	SAND	CHIPS	HALF	ONE	TOT
CURVE 3	QUANTITY (%vol)	15	25	15	25	20	100
	QUANTITY (%mass)	13,58	27,59	14,79	24,47	19,57	100,00

Figure 3.5: Design for the walls

These ratios gave the following cuve. We clearly observe a lack of sand and medium gravels according to concrete optimums. On the other hand,

the ratios of fine particles seem coherent.

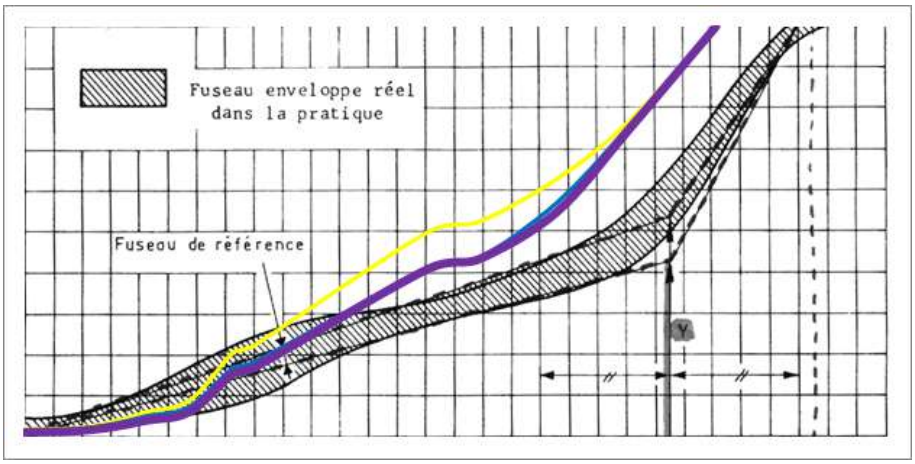


Figure 3.6: Design for the walls

3.3 About the method : conclusions

This tool is based on a french method for concrete design, written by engineers Dreux and Gorisse in :

Composition des bétons : méthode Dreux-Gorisse, G. Dreux et F. Gorisse, *Annales de l'Institut Technique du Bâtiment et des Travaux Publics. N°414. Beton 214. May 1983.*

It provides a complete method for the formulation of concrete, based on a wide range of experiments whose results where then gathered and analyzed to elaborate global procedures. The dry aggregate mix is part of it, and the curve that I should to use represent the average area for dozens of concrete, as a matter of gradation. I kept for this software two different curves, respectively corresponding to D<20mm and D<40mm, D standing for the size of the biggest aggregate. Here we will chose one of the other graph if we use 1" gravels (D<40mm) or not (D<20mm). I would conclude by saying that this software is now only an experimental tool, based on my own laboratory tests, with limited equipment (see the Sieve Analyzes report), and which therefore contains some errors an approximations. Also the comparison between poured earth and concrete should provide some hypothesis, leads and new ideas for next formulations, which would need to be compared with mechanical tests (shrinkage and compressive tests). It must not be used as a

design tool, as we still have no precise idea about "poured earth" characteristics.

Chapter 4

Compressive tests

4.1 Objective

A wide range of samples were designed and tested under compression strength. This file reports the results for 85 samples (61 cylinders and 24 10x10x10 cubes), giving their compressive strength respectively 7, 14 and 28 days after the day of pouring. We are testing here different ratios of aggregates (the dry soil/sand/gravel mix), in addition to different amounts of binder (cement or lime). Information about water required and workability reached are also included. We will therefore follow the evolution of the strength of these mixes according to the time of setting, and determine the best ratios of different materials which should be used in poured-earth.

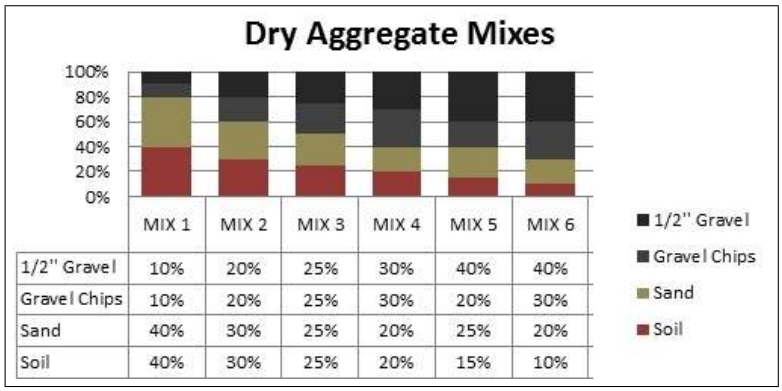
Figure 4.1: 1st range of samples : 1Cy and 1C series

4.2 Samples design

It was decided to produce samples containing 5%, 7,5% and 10% of cement and 7,5% of lime, added to the six different mixes designed in Chapter 1, as reminded on Fig. 4.2. The amounts of materials where calculated according to the volume required to make a slump test, then three cylinders [1] and

[1] 210x104 mm

one cube [2]. The cylinders would be respectively tested under compressive strength after 7, 14 and 28 days, whereas the cubes would be tested only after 28 days. Cement samples were cured during 28 days by humidification twice a day, while lime samples were simply left outside to dry. Details about the composition of dry mixes can be found on Figure 1.2



	MIX 1	MIX 2	MIX 3	MIX 4	MIX 5	MIX 6
1/2" Gravel	10%	20%	25%	30%	40%	40%
Gravel Chips	10%	20%	25%	30%	20%	30%
Sand	40%	30%	25%	20%	25%	20%
Soil	40%	30%	25%	20%	15%	10%

Figure 4.2: The six different dry agreggate mixes used for designing samples

4.3 Procedure for making of samples

Since the slump test required a consequent volume of admixture, in order not to waste it the pouring of the cylindrical samples for the compressive strength test was done just after. The casting of the cylindrical samples and the compressive strength test were all done according to the American standards ASTM C31. The cylinders used here were cut out of pipes and had a 21cm height and a 10,4cm diameter. It is necessary to have at least a height twice longer than the diameter, and the diameter of the cylinder should be at least 3 times the nominal size of the coarse aggregate used in the earth concrete.[3]

- The interior surface of the mould was oiled. Then the mould was placed on a ceramic tile in order to avoid adhesion when hardening and unmolding. The admixture was poured in two equal layers each tamped 25 times with a 1,6cm diameter rod.

[2] 100x100x100 mm

[3] For every mix, one cubic sample was poured in a cast iron mould, in addition to three cylinders made as explained above.

- The surface was leveled with a trowel. The samples were unmolded 3 to 24 hours after. The samples with cement were then cured for 27 days whereas the sample with lime were left outside for 28 days.
- After 28 days of curing for cement based samples, and drying for lime based samples, they were ready for the compressive strength test. [4]

4.4 Water content of the mixes

For every mix, the water is sensitively adjusted, according to the global workability of poured earth. Since the mix was done by hand and trowel in a simple wheelbarrow, and the sample poured manually and only tamped with a small rod (no vibration or ramming), it is clearly understood that 1:1 mixes will require less water. Indeed, using a concrete mixer and a vibrating needle will help a lot to diminish the ratio of water, therefore improve the strength and limit the apparition and growing of cracks in the structure. In spite of these lacks of precision, I tried every time to adjust the water in order to get a sufficient workably, i.e. allowing pouring in the molds. I estimated that a Slump of 5 to 10 (S2 Class), was the best, and tried to stick to this range of water contents. For every mix a Slump Test was realized, using the Abrams Cone.

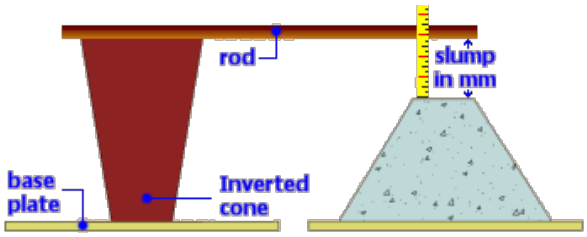


Figure 4.3: Water contents for S1, S2 and S3 Slump classes

Class	Slump range	Target slump
S1	10 ~ 40	20
S2	50 ~ 90	70
S3	100 ~ 150	130
S4	160 ~ 210	180
S5	210 ~ n/a	220

Table 1: Slump class from BS8500

Figure 4.4: Water contents for S2 and S3 Slump classes

We can sum up the results that we obtained for the water content, on the figure 4.5. It is here given in percentage, as the mass of water divided by the total mass of dry aggregates (excepted cement).

It is also possible to focus on the S2 and S3 classes only, since S1 mixes were slightly too dry to reach a really good workability (see Figure 4.6).

[4] Details and photographs about the procedure are to be found in appendix, page 65.

% WATER	10%<...<11%	11%<...<12%	12%<...<13%	13%<...<14%	14%<...<15%	15%<...
S123						
RATIO	4	1,5	1	0,67	0,67	0,43
C 5%	13,93%	14,91%	13,32%	12,11%	11,12%	10,03%
C 7,5%	15,87%	14,27%	12,73%	11,83%	12,56%	
C 10%	15,79%	14,30%	13,46%	12,67%	11,66%	
L 7,5%	18,28%	15,86%	13,21%	14,17%	13,50%	

Figure 4.5: Water contents for S1, S2 and S3 Slump classes

% WATER	10%<...<11%	11%<...<12%	12%<...<13%	13%<...<14%	14%<...<15%	15%<...
S23						
RATIO	4	1,5	1	0,67	0,67	0,43
C 5%		14,91%	13,32%	12,11%	11,12%	
C 7,5%					12,56%	
C 10%		14,30%	13,46%	12,67%	11,66%	
L 7,5%	18,28%	15,86%	13,21%	14,17%	13,50%	

Figure 4.6: Water contents for S2 and S3 Slump classes

First we can notice that the water required evolves according to the composition of the mixes, especially with the ratio soil/aggregates. The more soil we add, the more water we have to add to the mix. This is due to clay particles, which will absorb a lot of water and swell. Therefore it is required to add more water in order to complete the hydration of cement and to get a sufficient plasticity for pouring. Since clay is swelling, it is also not so good to add to much water, because of the shrinkage phenomenon which will appear while drying, and cause cracking in the structure. The second aspect which it is important to take into account is the fact that the samples made using lime require much more water than those made with cement. In fact, adding lime to soil will strongly increase its limit of plasticity, so it will be necessary to add water if we want to reach a workability class similar to cement-samples. This is of course a bad deal for a poured earth mix, as we explained above.

4.5 Estimation of the density

Prior to compressive tests, the samples were weighed, dried in the oven then weighed again. This procedure usually gives good informations about water

content, but since the samples were cured every day (i.e. water was spread twice a day, thus in order not to allow them to dry), any information about their water content is not really relevant here. However, it is interesting to gather results in term of density after drying : indeed, to reach a good strength, any concrete sample should be the more compact as possible.

Therefore the samples were weighed after drying : the results in term of density are given on Fig.4.7 for the cylinders and on Fig.4.8 for the cubes.

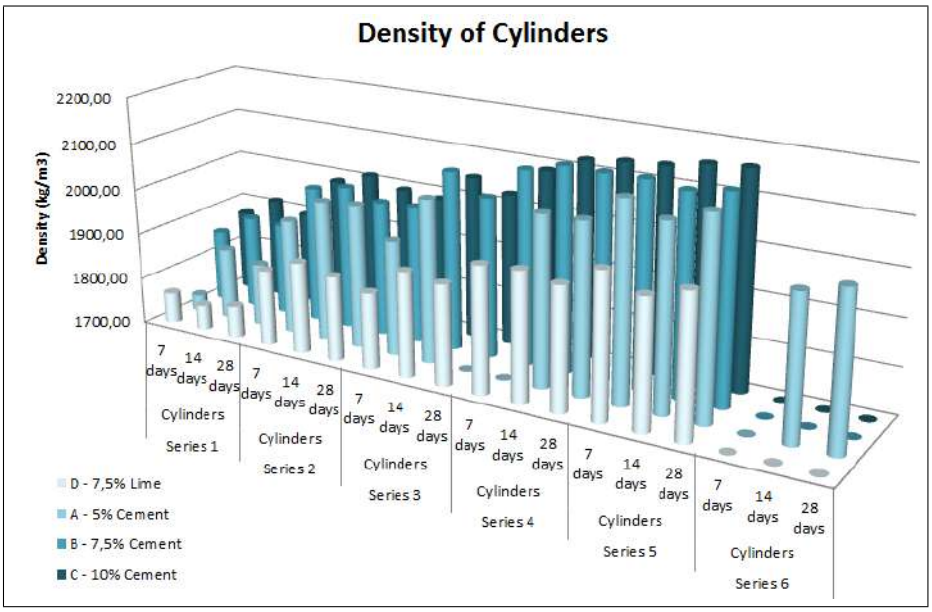


Figure 4.7: Values of density measured on cylindrical samples

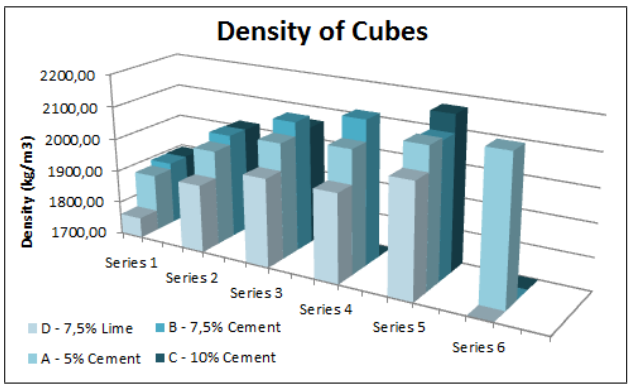


Figure 4.8: Values of density measured on cubic samples

We can conclude for these two graphs that among the different mixes that we designed, the density increased with the ratio of gravels (gravel chips

and half inch gravels) : for example the dry mixes 4 and 5. As in a concrete, whose density is on average between 2000 and 2600 kg/m^3, the more compact the sample is, the most important compressive strength it will reach. We can also notice that the nature of the binder seems to play an important role in the final density : the samples containing cement are much heavier than those containing lime. It is also interesting to notice that the quantity of cement does not seem very influent: adding more than 5% cement will not consequently increase the final density of the sample.

4.6 Compressive strength

The compressive strength test were performed on the manual hydraulic press of the Institute, according to the test protocols in force here. The samples are places between two plates of steel, and the load is manually increased by moving up the bottom plate, until the sample breaks. It is then possible to measure the maximum load thanks to the stress gauge included.

4.6.1 Failure modes

The cylinders and the cubes were loaded until we could observe the failure of the sample. Different failure modes can occur : for the cylinders, we generally observe a cone-shaped failure. When the tensile strength inside the sample gets to important, shear stress can trouble the trial and cause a diagonal crack, known as "shear failure"[5]. It is advisable to avoid this phenomenon by being careful to accurately center the sample on the plates, otherwise the failure will occur before reaching th real compressive limit, therefore providing biased results.

4.6.2 The case of lime

It clearly appears in all the different tests and for all the dry agreggate mixes used that lime is a very poor binder for poured earth. After 7, 14, 28 and even 56 days[6], the samples never reached a minimum of 1 MPa, and most of the time the machine did not even record any load when breaking. Once broken, they could be easily crushed by hand, as if there was no binder at all inside (cf. Fig. 4.9).

[5]Refer to appendix .4.3, page 68 for more details and pictures of these examples
[6]A previous sample left at the Institute by Alberic Lehuede was tested after 56 days

Figure 4.9: Illustration of the friability of the samples made using lime

4.6.3 Results on cylinders

We can first sum up the different results obtained for the cylindrical samples on the Fig. 4.10. It is clear that the compressive strength of poured earth

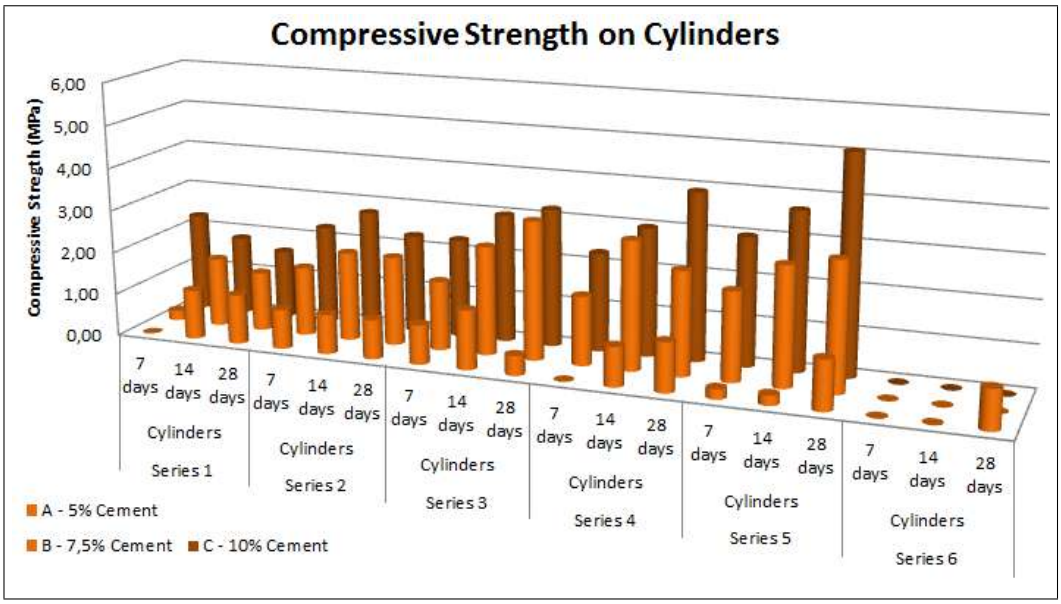


Figure 4.10: Compressive strength obtained on cylinders

increases when the ratios of gravels are increased and the amount of soil decreases. Globally, the resistances vary between 1 MPa and 5 MPa, according to the different amounts of materials and stabilizer.

Percentage of stabilizer and curing process

Tests were conducted for all the different mixes with different amounts of stabilizer[7]: while we only used 7,5% lime, we also designed samples with respectively 5%, 7,5% and 10% cement, in order to be able to find out which quantity of cement was the optimal one. After pouring, samples were cured every day, and broken after 7, 14 and 28 days. The results[8] corresponding to these different parameters are given on Fig. 4.11. As for classical concretes,

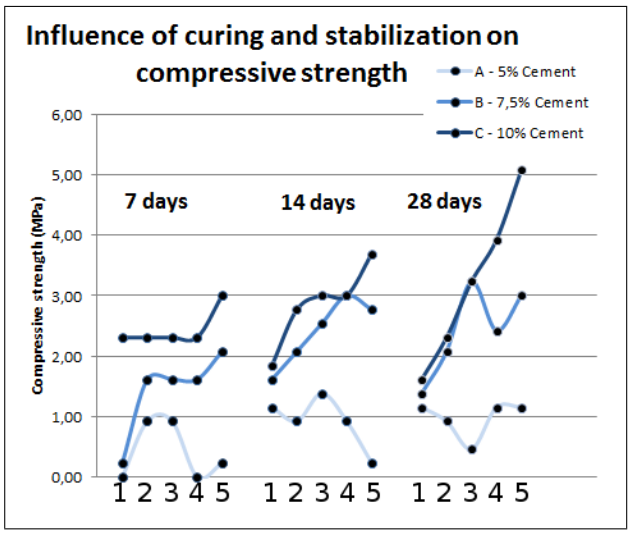


Figure 4.11: Variations of strength with curing time and quantity of cement

the genuine resistance of the sample is reached only after 28 days. During this period it is important to maintain a certain amount of water inside the materials, for the chemical reactions in cement to occur, and binding the agreggates together. It seems obvious that the more cement and gravels are added, the more final resistance we will obtain, while important ratios of soil seem to weaken the final strength. It will be then important to clearly define the desired resistances to formulate a poured earth mix...

4.6.4 Results on cubes

It was decided also to manufacture cubes for the different mixes tested under compressive strength : one cube per mix was made, and cured during 28 days

[7] Refer to Fig. 4.2, p. 31 for their exact composition

[8] Results are given only for the series 1, 2, 3, 4 and 5 since the sixth contained too much gravels, disturbing its manufactering. Moreover, since its soil ratio is very small, it is not a relevant formulation for "poured earth".

before testing with the same hydraulic press. The results of the tests are to be found on Fig. 4.12 We observe the same tendancy than with cylinders :

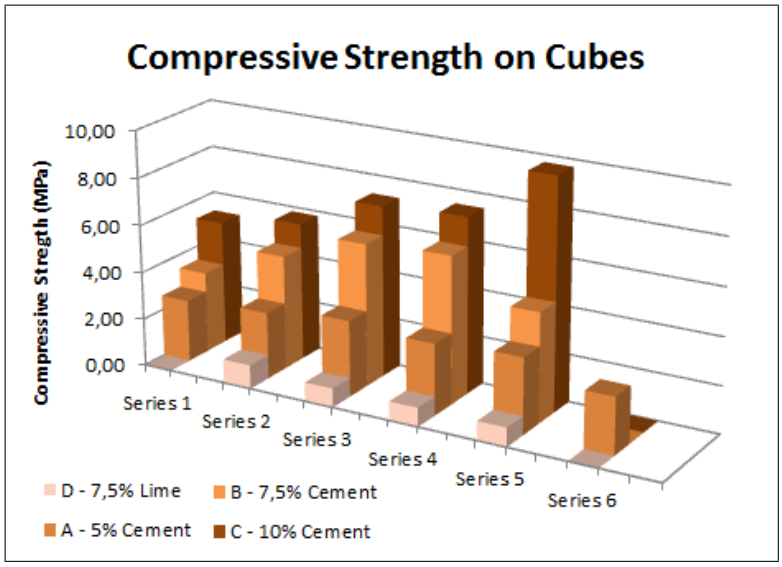


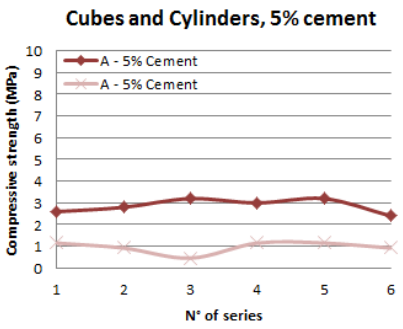
Figure 4.12: Compressive strength obtained on cubes

the best resistances are reached by the samples containing less soil, and more gravels and cement. Therefore the same conclusions can be drawn.

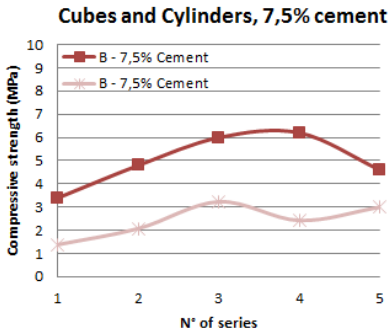
4.6.5 Comparison between cubes and cylinders

It can be interesting to try to characterize more precisely the results provided by cubic and cylindrical samples : indeed, if they seem to give the same kind of results about the ratios of materials and binders, the results obtained under compressive strength are not exactly the same. The same global tendancy is obtained, but we can also notice (see Fig. 4.13) that the compressive strength of cubes is much higher than that of the cylinders. This result is well-known for concrete samples[9], and we can notice that it is also valid for poured earth. Moreover, the cylinders used for these tests were of small dimension (21 cm height and 10 cm diameter): which is not enough to sufficiently get rid of the troubles due to shear stresses. I suggest in the future to focus only on cubic samples, since they seem to be more accurate.

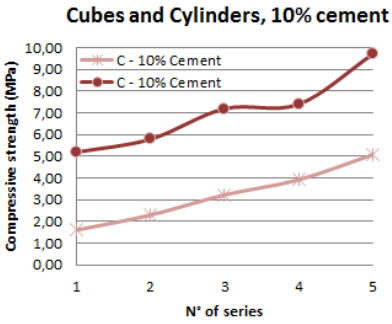
[9]e.g. if we observe a resistance of 20 or 30 MPa on a cylinder, we will respectively find 25 and 37 MPa on a cube made of the same concrete



(a) Part 1



(b) Part 2



(c) Part 3

Figure 4.13: Results on cubes and cylinders

4.7 Estimation of the Young's Modulus

The results obtained by processing compressive strength tests only provide stress in the material when it breaks. This value is interesting, but it does not give any information about its general behavior. I wanted to go further, and to characterize more precisely poured earth, mainly in term of elasticity and plasticity: therefore I decided to run some simple compressive tests, using a "home-made" device to obtain the elasticity limit of the samples, also known as "Young's Modulus". These tests were performed on 10x10x10 mm cubes, after 28 days of curing.

4.7.1 Tests on poured earth

Protocol for testing

A compressive strength test was performed just as for classical tests, but a dial gauge was fixed to the machine in order to measure the displacement of the bottom plate, thus the inner deformations of the sample. By regularly

taking pictures of the machine, it is possible to get at the same time the stress and strain dials, then to draw the corresponding stress-strain curves. I used Microsoft Excel for this part, reading and entering manually the values of load and displacement. Please refer to appendix .4.4, page 69 for photographs and explanations.

Results

After importing the different values, we can draw the stress-strain curve for every samples, as o Fig. 4.14. We can observe that the general shape of the curve follows the classical laws : an elastic area with its limit, then a plastic area which ends with the failure of the sample. Despite this interesting

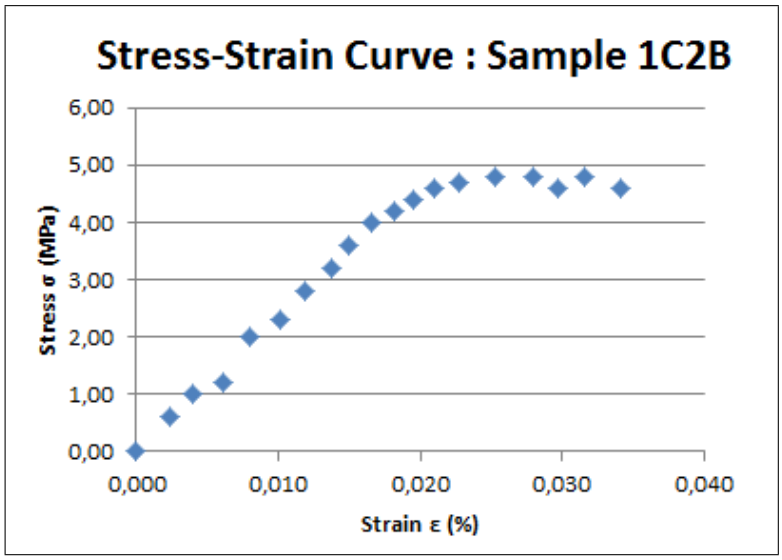


Figure 4.14: Example of strain-stress curve for a cube

results, there seems to be a problem when we try to estimate the Young's Modulus of poured earth, since all the results are giving values in a range between 100 MPa and 500 MPa, which is way too low according to average values[10]. So we can challenge the procedure, and wonder if an error occured in the tests...

4.7.2 Tests on steel

Seeing the results given by the different cubes of poured earth tested under compressive strength using AVEI "Shiva" machine, I decided to make some

[10]Young's modulus for concrete is between 20 and 50 GPa...

additional trials using a well-known material. Therefore I ordered a 50x50x50 mm cube at Aureka (Auroville's steel construction workshops). I managed to obtain a S235J0 steel, whose mechanical average characteristics are given below.

Minimum Yield strength (thickness between 40 and 63 mm): $215 N/mm^2$

As for classical steels, the Young's Modulus should be approximately of 200GPa. Performing compressive tests on the cube should give us a comparison between this theoretical value and the results obtained experimentally.

Protocol for testing

Four trials were conducted for this experiment : the cube was first compressed twice between two sheet of cardboard (thickness of 3 mm), then twice with no sheet, directly between the two steel plates of the machine. Compression was stopped when the indicator reached 350 kN (about 140 MPa), two avoid any plasticization and stay in the elastic area of the material.

Results

The strain-stress curves corresponding to the four tests can then be drawn on a same graph (see Fig. 4.15)[11]. We can notice that the behavior of the cube is not the same whether or not cardboard is used for testing protocol. Without cardboard, we observe a linear evolution between stress and strain, while the curves with cardboard seem to follow an exponential evolution... From this we can conclude that cardboard could represent a real problem for the accuracy of measures, since it will trouble the general aspect of the curve. To go further, we can draw the same curve by eliminating their non-linear areas, i.e. the first part of loading, when important displacements occur in the cardboard sheets. Therefore it is possible to evaluate the Young's Modulus of the material, corresponding to the slope of this line, on Fig. 4.16. We can read on the graph four different values for this modulus of elasticity, which are quite close. Also the presence of cardboard does not seem to have a real influence on Young's Modulus reading. What remains strange is the fact that we obtain a modulus of about 5000 MPa, while it should reach for common steels about 200 GPa (40 times more!). This test confirms the fact that our

[11] The curves referred as "Steel 1" and "Steel 2" stand for the cube with cardboard, while "Steel 3" and "Steel 4" stand for the same cube of steel with no cardboard.

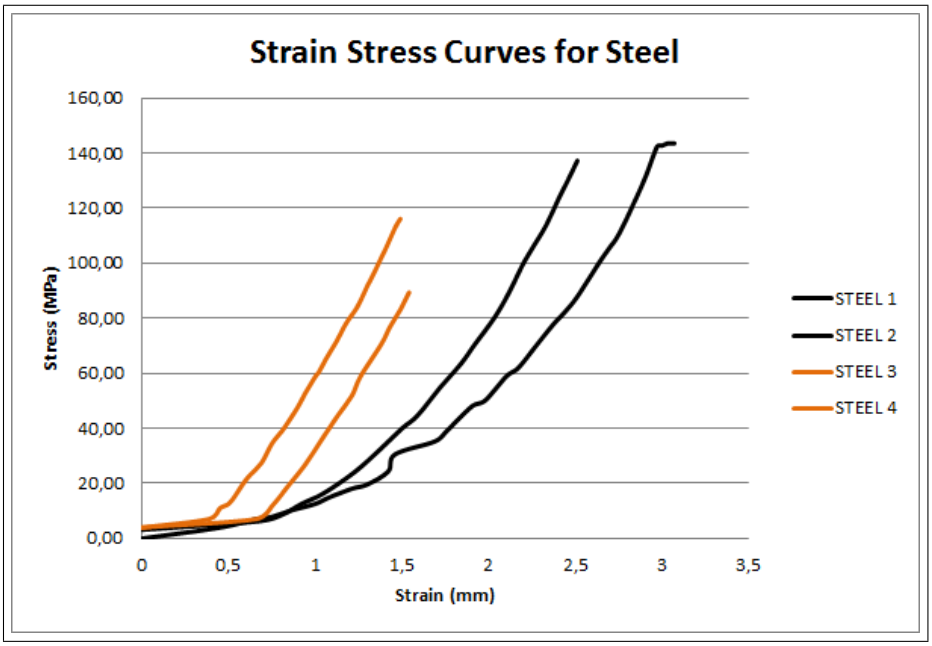


Figure 4.15: Strain-stress for a 50x50x50 cube of steel

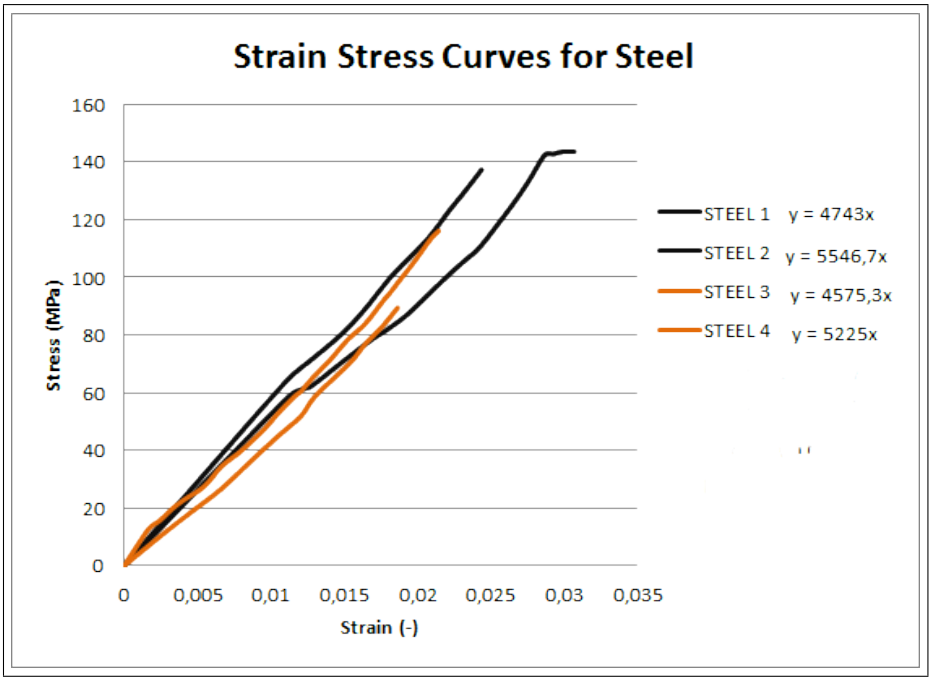


Figure 4.16: Strain-stress for a 50x50x50 cube of steel : linear area

protocol of testing does not provide a suitable method for evaluating the elasticity of materials.

4.7.3 Conclusions about Young's Modulus

In spite of testing a lot of different cubes, comparing with a well-known material (steel) and always trying to improve the testing methods, e.g. by designing a system with the dial gauge, trying to find out whether or not cardboard played an important role in the measures, I remained unable to get accurate and coherent results in matter of elasticity. However, knowledge on the behavior of poured earth is fundamental, and we cannot be satisfied with the only values of shrinkage and compressive strength. Finding out why these trials failed, and finding a way to improve the measures and obtain relevant values of the Young's Modulus would be an important step.

Chapter 5

The walls

5.1 Introduction and objective

During the second part of my internship, and regarding the results already obtained on the different samples, it was decided to pour real walls of dimensions 24*120*225 cm. Three different walls were made, using different ratios of materials, as described on Fig. 5.1[1]. They were all stabilized with 7.5% cement out of total mass. The main objective of these experiments was to test the realizability of poured earth walls on site, with heavy equipment[2] and a team of four to five workers. We also aimed to measure the final shrinkage of the walls, and to observe the apparition of cracks inside the structure after drying. It was also decided to cure the walls during the 28 days following their manufacturing.

	Wall 1	Wall 2	Wall 3
Soil (L)	25%	20%	15%
Sand (L)	25%	20%	25%
Gravel Chips (L)	15%	20%	15%
1/2" Gravels (L)	15%	20%	25%
1" Gravels (L)	20%	20%	20%

Figure 5.1: The three different dry agreggate mixes used for designing walls

[1] Giving only ratios for agreggate mixes, without cement
[2] Formworks, vibrator...

5.2 Procedure for pouring a wall[3]

All volumes of dry aggregates required were measured using buckets and wheelbarrows, while the precise mass of cement was weighed. All materials were manually mixed by three persons, directly on the floor, which had previously been saturated to avoid soaking of water by the soil thereafter. Then water was gradually added to the mix, while slump-tests were performed until it reached a sufficient workability for pouring[4].

The final mix was then poured by hand in the formworks which had previously been installed, oiled and made wet. It is important to pour the mix in 20 to 30 cm layers, which should be properly vibrated using a mechanical vibrator. This process was conducted until the top of the formwork was reached. Then the wall was perfectly leveled with trowels and floats.

The final wall was then covered with a plastic sheet to avoid drying, and left for setting. The formworks were removed after 24 hours; water was then spread on the walls, which was covered again with a plastic sheet for three additional days. Next 28 days, the wall was cured every day by spreading water on its surface.

Figure 5.2: The three walls after unmolding and 28 days curing

5.3 Results and comments

5.3.1 General comments

All the three walls appear on Fig. 5.2. We can see that after curing there was no cracks on their surface, which is very smooth. The poured earth mix

[3]Please refer to Appendix .5, p. 70 for all the correponding pictures.

[4]It was observed that a 2 to 3 cm slump was sufficient, since the mix was then vibrated

set very fast, since it was possible to unmold it only 24 hours after pouring; at this time, a test performed with a penetrometer indicated that the wall had hardened quickly.

I could not get in time the results in term of compressive strength, but one 20x20x20 cm cubic sample was made for each wall, which should be now broken to get an idea of their resistance. It could be interesting to compare with the results obtained on cubic and cylindric samples, since the walls used less water, and were vibrated instead of tamped, allowing a much higher final density.

5.3.2 About water

I could notice that thanks to the use of a vibrator on site, it is possible to reduce consequently the amount of water in the final poured earth mix. If we compare the results with those we got while manufacturing samples (see Fig. 4.6 and 4.6 p. 33), we can note a significative difference with those reported on Fig. 5.3 for the walls.

Ref.	**Wall 1**	**Wall 2**	**Wall 3**
Amount of water	10.45%	10.33%	10.25%

Figure 5.3: Quantity of water used for the walls

While we required up to 12 or 13% of water when making samples, we see here that an average of 10.3% only was used for the wall. Therefore we can conlude that the use of vibration is very interesting, since it will reduce the final shrinkage of the structure together with the water initially included in the mix...

5.3.3 Final densities

Ref.	**Wall 1**	**Wall 2**	**Wall 3**
Expansion rate	0.61	0.54	0.53

Figure 5.4: Expansion rates for the walls

Because of the physical properties of the different materials, which all have different gradations (see chapter 2), the final density of the walls is more important than the different specific densities of the aggregates. Therefore

the final volume of the mix is less than the sum of the volumes of its different components. It is then interesting to define the expansion rate of every walk: I estimated it by dividing the final volume of mixture by the sum of the volumes of the agreggates included. The results are to be found on Fig. 5.4, were we can see that the optimum of density is reach for the third wall, corresponding to the dry mix n°5 (see previous chapters for more details).

5.3.4 Conclusion

These three walls were the first real scale project conducted in the Institute on poured earth. Since we managed to produce walls presenting a good surface, a sufficient resistance of several MPas, with a good workability and an easy process for pouring, allowing to work very fast with only a few workers, we can say this experiment is a great success. Indeed it proves that poured earth is a credible alternative to CSEB, and that it is now possible to go further in this way, using the technique for real construction.

On the other hand, it could be argued that the only thing we made it is reinventing concrete. It is true that the composition of our walls is clearly that of a classical concrete mix, in which a certain amount of soil would have been included. This giving of course interesting results, but way lower to those we would have obtained on a real concrete. Therefore the next trials should be focusing on how to include higher amounts of soil in the mix while preventing the shrinkage to increase and the compressive strength to decrease. Reducing the total amount of cement would also be an interestig lead, maybe by replacing it by other binders, or using additives...

Chapter 6

Additional samples

6.1 Objective

Regarding the results given in chapter 4, I decided to conduct some other tests, including in the poured earth mixes different amounts of other materials, binders or additives. Among the different experiments I made, is the use of plaster of paris as binder instead of cement, or crushed firebricks instead of soil... Unfortunately I had not enough time to properly design a sufficient range of samples and test them ater 28 days. I could only collect data after 14 days, therfore the final results are not really relevant, and I won't include them in this report[1]. I will only describe the new ideas and leads that I imagined, designed or tested during the last weeks of internship. Some of them could be interesting to follow in the future...

6.2 New leads for poured earth mixes

6.2.1 Plaster of Paris (P.O.P.)

As an interesting alternative to poured earth, we can find in the world different projects conducted on Cast Earth, mainly in America[2]. Using a small percentage of P.O.P. as binder (around 15%), it seems to be possible to reach very important resistances under compressive strength (up to 20 MPa according to the builders). It is then possible to erect entire buildings with this cast earth. Its main strength is, unlike concrete, to be compatible with soil, since the fine particles (silt and clay) don't counteract its effect. But, while

[1] The complete calculus and data sheets corresponding to this chapter can be found on the AVEI server

[2] See for example http://www.castearth.com/

cement and lime are reacting well with water and moisture years after building, P.O.P. is very sensitive to humidity, and only suitable to dry climates. Therefore the south of the U.S.A. is the perfect place for broadcasting this technoogy, while India does not seem to be so appropriate.

Still, it is observed that gypsum is often used for stabilization of soils, mainly in the agricultural field. Therefore we can wonder if one or another form of gypsum (such as P.O.P.) could play an interesting role in mixes, as stabilizer or binder. It would be interesting to proceed to a whole range of tests, using different amounts of P.O.P., to confirm or infirm this hypotheses. Another problem is the setting time of P.O.P., which becomes hard within 5 minutes, making cast earth very difficult to work with. Other components retarding its setting should then be looked for...

6.2.2 Crushed firebricks

The origins of mortar and concrete are to be found in the antic Rome, where crushed fired tiles were included in the mixes, confering them much higher strengths. I wondered if heating the soil at high temperatures would change its physical and chemical composition, and making more suitable for poured earth. Therefore I crushed local firebricks, made of the same soil available in Auroville, and used it instead of raw earth. I could only pour two samples, which is not enough to draw any conclusion, but the results on these samples were not lower than those obtained with raw earth. It could be an idea to carry on with these tests, even if I am not convinced that it is the best lead to follow...

6.2.3 Lime + Cement

I could not design any experiment for this lead, but I had the idea it could be interesting to use both lime and cement. Cement acts in poured earth as a binder, but its effects are partially counteracted by the fine particles, particularly by clay. Therefore it seems to be a possibility to use lime as a stabilizer, seeing its well-known effects on clay, in addition to cement which would still play the part of binder. I would recommand to try 1% lime + 5% cement to begin with.

6.2.4 Chemicals and additives

In the concrete industry, many additives have been found to improve the properties of concrete mixes. Reducing the water content, increasing the densities and the compressive strengths, retarding or accelerating the setting,

improving the workability are some examples of great improvements made during the last years of research. Since poured earth aims to be a green, cheap and durable way of building, I would totally proscribe the use of artificial chemicals. It is tempting to employ water-reducers and super-plasticizer, but since we are trying to work with small quantities of cement, their effect is very relative, and their employment not advisable.

On the other hand, it would be very useful to manage to deflocculate the particles in soil, thus consequently allowing to reduce the volumes of water. Washing powder or soapnut work well for this purpose[3], since they decrease the pH of the mix, breaking the electrical bounds between water and clay. On the other hand, it seems that a low pH counteracts the effect of cement; the samples become very weak under compressive strength. Some research is conducted in France on this topic, and interesting results have been carried out by a team of CRATerre/MATEIS INSA Lyon with wood ash for example. It is advisable to follow their work and exchange with them in the future...

[3]See Alberic Lehuede's report for more information

Chapter 7

Conclusion

The R&D project on poured earth still has a bright future ahead, since there are still many things to discover. I tried during this internship to follow different leads, between concrete and earthen construction. Some interesting results were found, some others turned out to be ways to forget about. Anyway, I could define and draw new lines of work, and lay the foundations for next steps.

Laboratory tests were carried out on all aggregates, and complete sieve analyses were performed. One of the key for poured earth will be to design a perfect dry mix, therefore we will need to adjust the gradation of soils, which may vary from one place to another, in order to make it suitable for our purpose. It is fundamental to get first a perfect knowledge about the composition of all the materials involved in the process: sand, gravels, soil. Additional specific laboratory tests should be conducted for soil, to know more about its behavior[1].

Manufacturing an important range of samples (near 100 samples in two months) and regularly testing them under compressive strengths allowed us to get more information about the mechanical behavior poured earth, which is close to concrete. We learnt that it is possible to reach important resistances (up to 10 MPa on cubes), but it is now required to precisely define our attempts. It is now important to include a maximum amount of soil in the mixes, without decreasing too much the compressive strength, thus to define a compromise between the ratios of aggregates that we want to use and the mechanical properties acceptable.

[1] I would suggest to perform wet sievings, sedimentation, blue methylene and Atterberg's limits tests. Not only they allow to get a good overview of the composition of the soil, but also they guarantee the comparability of all kinds of results with other laboratories in the world, since we use national or international standards. I performed all these four tests during my internship, which can be found on AVEI server.

In continuity, it is now time to continue real scale work: the first steps have been taken with the realization of three walls. The results obtained on samples should allow now to include more earth in the mixes, decrease the amounts of cement, and build longer structures with less shrinkage. The methods could be then adapted on site, and used on a bigger scale. The interaction of steel and poured earth is still to be tested.

Chapter 8

Next steps

- I started performing different soil tests, which are of four kinds, according to the standards designed by CRATerre, which are available on the server : wet sieving, sedimentation test, blue methylene test and Atterberg's limits. It is advisable to go on with these tests and record all the results for Auroville Earth Institute's Earth. It would be then very useful when sharing experimental results with other laboratories, such as CRATerre where people recommended me to conduct these tests.
- It could be interesting to test other binders than cement: I wanted to follow the lead of Plaster Of Paris, which is known to provide good results under compressive tests, and no shrinkage when drying. Though it does not react well with moisture, it would be worth making some additional tests.
- Lime seems to be a very poor binder for poured earth; however it would be interesting to use it as a stabilizer for clay in small quantities, in addition to cement as a binder. For example trying a 1% lime 5% cement mix could be very interesting.
- New walls should be made, decreasing the amount of stabilizer and increasing the amount of soil. I would advise to focus on a 50% soil 50% aggregates for next tests, since the three experimental walls made so far where more concrete than "poured earth".
- Interaction steel/poured earth has not been explored now: some samples could be designed for traction/compression and adherence evaluation.
- All tests so far were conducted on dry sample: testing wet compressive strength could be very good in the future.

- I have been trying to determine Young's Modulus on poured earth samples, but failed in getting relevant results. This work should be continued until finding out where the error came from, and finally getting accurate data.

- Research is going on in France on poured earth: the way of cement stabilization has already been explored by CRATerre, and different people from INSA de Lyon (MATEIS lab) are currently conducting laboratory tests to find new leads for stabilization and deflocculating. Some parts of their work is already available (see the corresponding folders), and I have been in contact with them during all my internship. It would be good to keep in touch in the future and exchange results.

- Last but not least, finding some partnerships between the AVEI and industrial firms (such as cement manufacturers) could be very useful for the development of poured earth. The green aspect of this technology as its similarities with the concrete industry is an interesting way to explore, since it could unlock funds and allow to launch new projects...

Appendices

.1 Introduction

The following pages are an addition to the report, and contain various complementary elements such as graphs and photographs which illustrate this research project conducted on poured earth. Mainly it will give the reader additional information about field and lab tests, and technical aspects of the work.

.2 Appendix to Chapter 2

.2.1 Procedure for sieve analyes(cf. Fig. 1)

- All sieves are weighed while empty.
- Sieves are piled up to form a column, from biggest (up) to tiniest (bottom) mesh. An additional cup is placed at the bottom.
- Upper sieve is filled with 1kg of dry material (e.g. soil, sand or gravels), then covered.
- Sieves are placed on the machine, which will shake the system for approximately 1mn.
- Sieves are removed from the machine, then weighed one by one after manually completing the sieving, using a simple brush.

(a) Filling sieves

(b) Placing sieves on the shaker

(c) Weighing Sieves

Figure 1: Sieve analyses

.2.2 Sample calculation sheet

SAMPLE : SAND2
DATE : 17/08/2011
Test performed by : Jerome

QUANTITY (g) of dry material : 1000

Number	Mesh (mm)	Empty Weigh (g)	Full Weigh (g)	Quantity in sieve (g)	Cumulated refusals (g)	Cumulated underflows (g)	Cumulated underflows (%)	Cumulted refusals (%)
-	20,000	0	0	0	0	994	100,0	0,0
-	10,000	344	344	0	0	994	100,0	0,0
-	5,600	420	426	6	6	988	99,4	0,6
200	3,000	434	454	20	26	968	97,4	2,6
170	2,000	256	278	22	48	946	95,2	4,8
50	0,500	462	1042	580	628	366	36,8	63,2
-	0,425	354	388	34	662	332	33,4	66,6
30	0,300	432	692	260	922	72	7,2	92,8
-	0,212	348	394	46	968	26	2,6	97,4
-	0,106	292	316	24	992	2	0,2	99,8
-	Bottom	282	284	2	994	0	0,0	100,0
TOTAL		3624	4618	994				

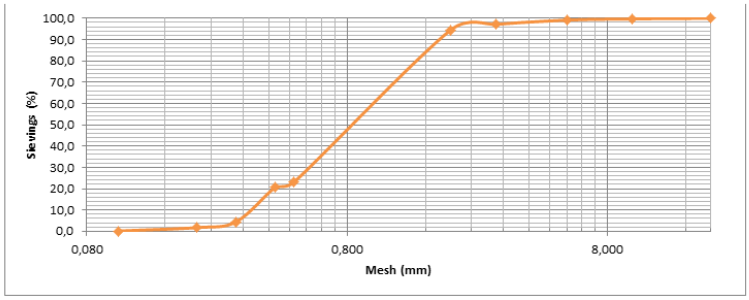


Figure 2: 1st range of samples : 1Cy and 1C series

.2.3 Gradation curves for all materials

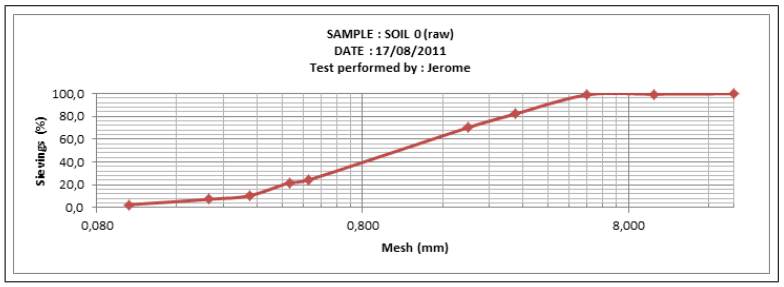


Figure 3: Soil 0

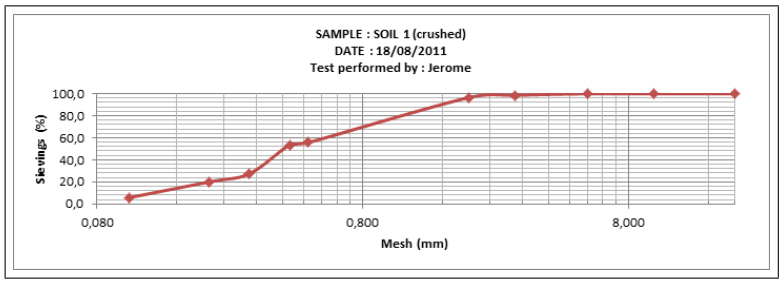


Figure 4: Soil 1

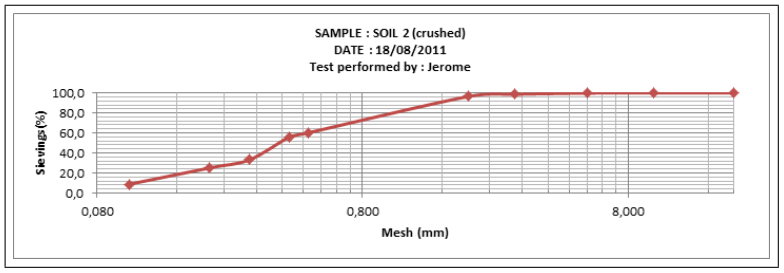


Figure 5: Soil 2

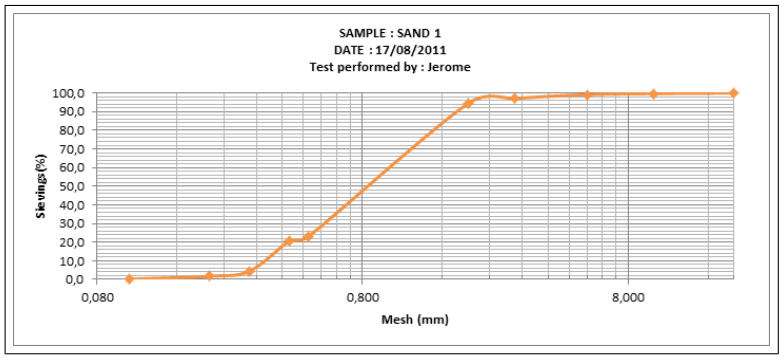


Figure 6: Sand 1

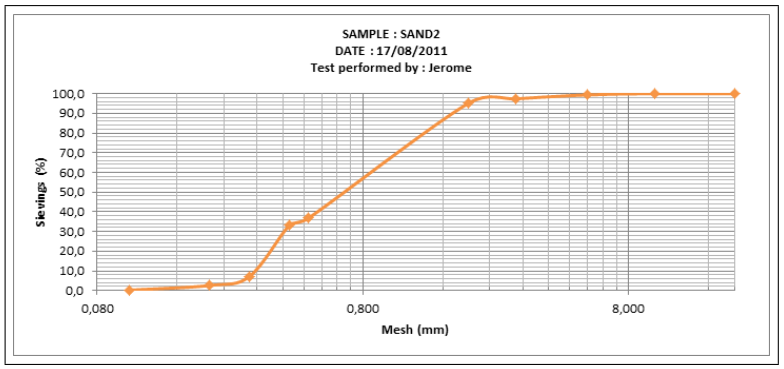


Figure 7: Sand 2

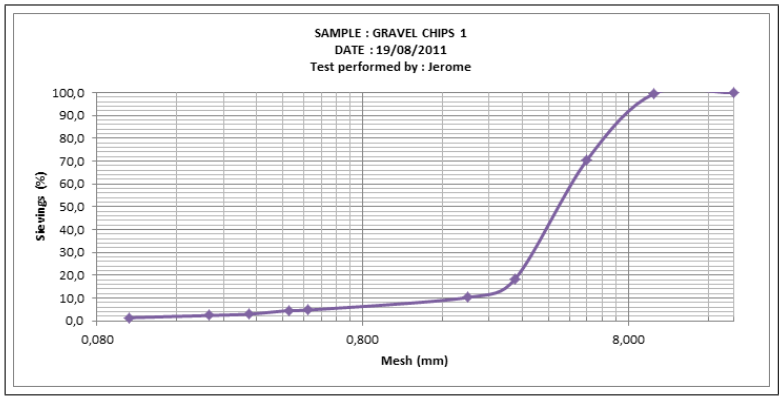


Figure 8: Gravel Chips 1

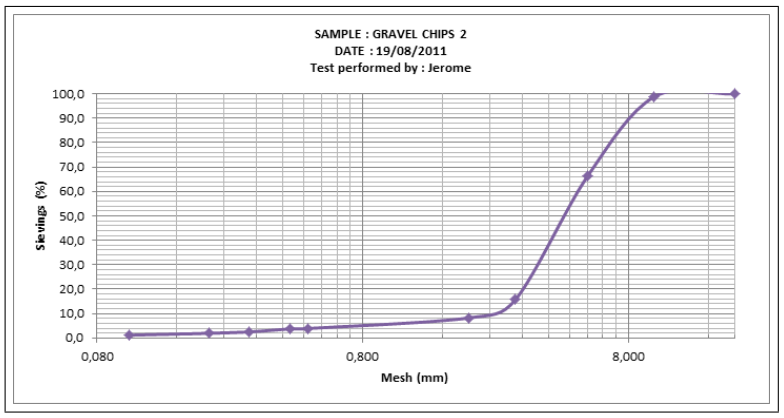


Figure 9: Gravel Chips 2

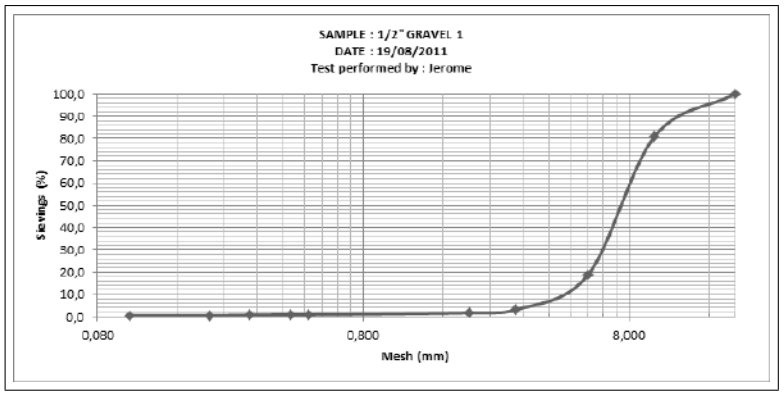


Figure 10: Half Inch Gravels 1

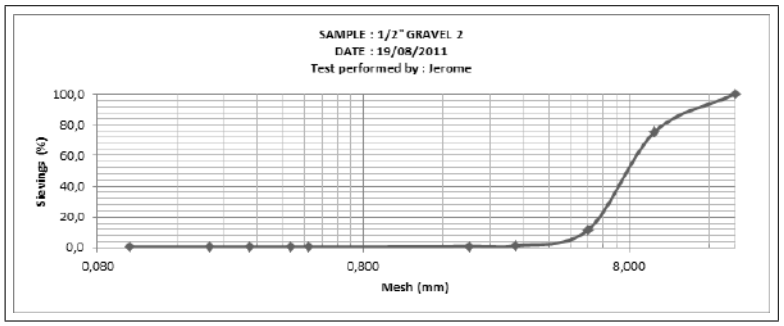


Figure 11: Half Inch Gravels 2

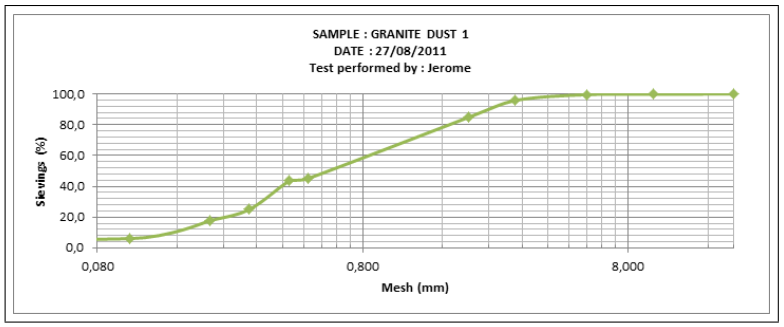


Figure 12: Granite Dust 1

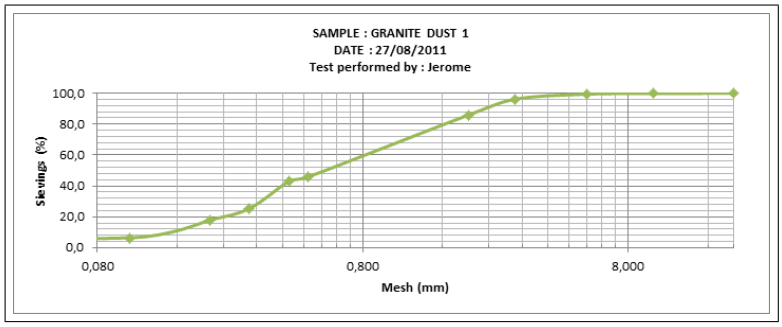


Figure 13: Granite Dust 2

.3 Appendix to Chapter 3

.3.1 Dreux and Gorisse method: ideal gradation areas for concrete mixes, D<20mm and D<40mm

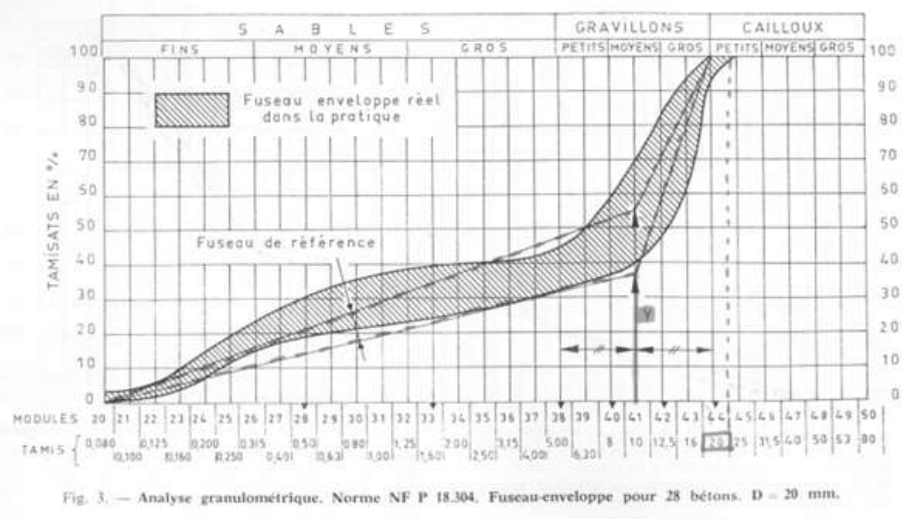


Fig. 3. — Analyse granulométrique. Norme NF P 18.304. Fuseau-enveloppe pour 28 bétons. D = 20 mm.

Figure 14: D<20mm, ideal area located as "Fuseau de référence"

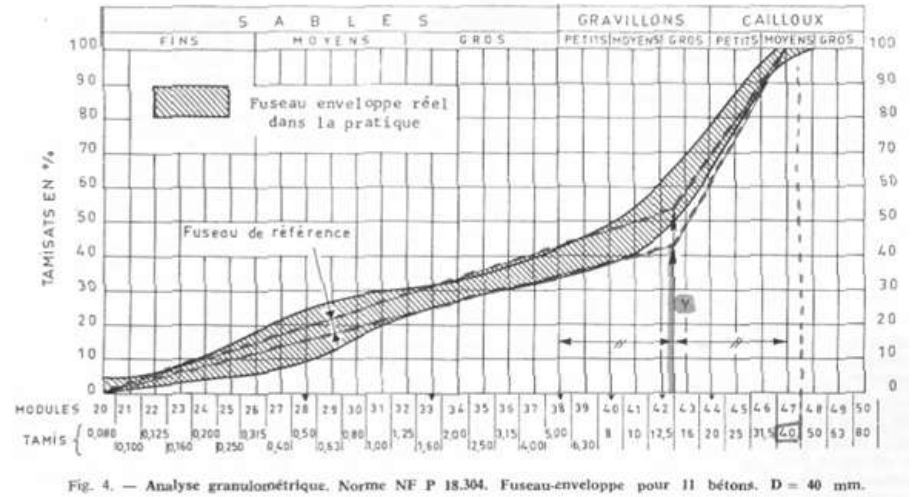


Fig. 4. — Analyse granulométrique. Norme NF P 18.304. Fuseau-enveloppe pour 11 bétons. D = 40 mm.

Figure 15: D<40mm, ideal area located as "Fuseau de référence"

.3.2 Views of the tool interface

Figure 16: Interface

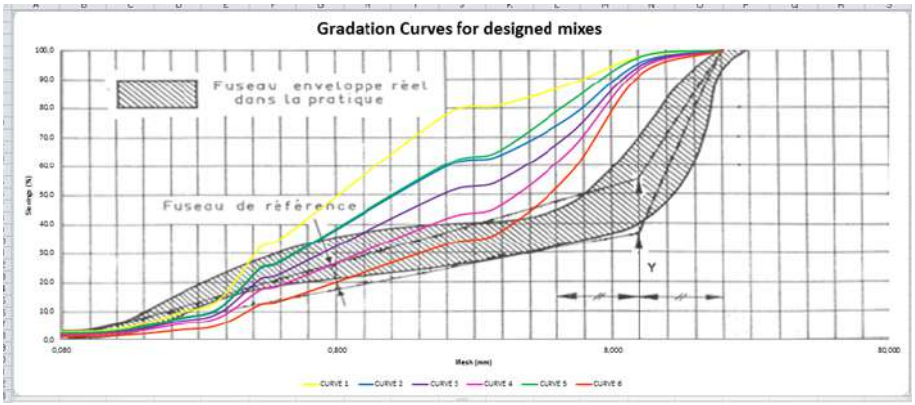


Figure 17: Interface

.4 Appendix to Chapter 4

.4.1 Procedure for making samples

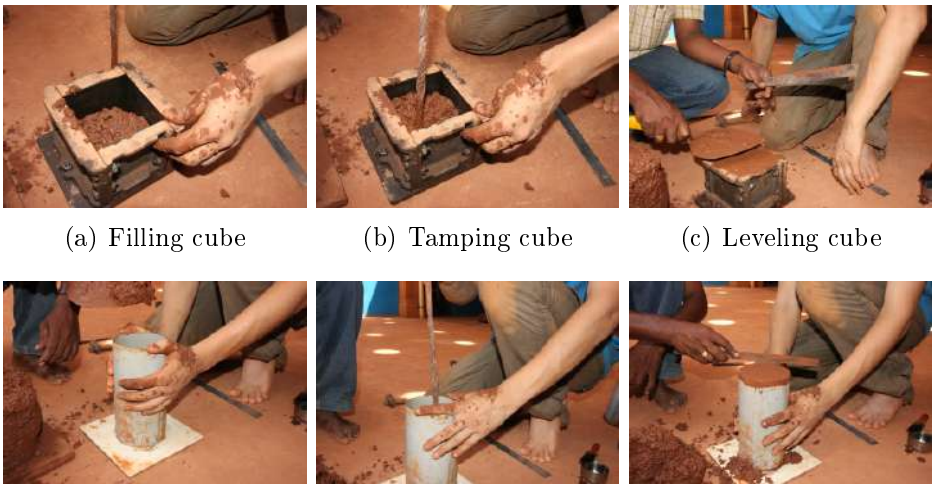
(a) Equipment (b) Dry agreggate mix (c) Mixing

(d) Adding water (e) Wet mixing (f) Oiling Abram's cone

(g) Filling Abram's cone (h) Tamping three layers (i) Removing the cone

(j) Measure of the slump (k) Oiling cubic mold (l) Oiling cylindrical mold

Figure 18: Sample making (1)



(a) Filling cube (b) Tamping cube (c) Leveling cube

(d) Filling cylinder (e) Tamping cylinder (f) Leveling cylinder

Figure 19: Sample making (2)

.4.2 Close-ups on the different samples (series with cement)

(a) 1CCy1 a b c

(b) 1CCy2 a b c

(c) 1CCy3 a b c

(d) 1CCy4 a b c

(e) 1CCy5 a b c

(f) 1CCy6 a

Figure 20: Series 1CCy

.4.3 Tests under compressive strength : cylinders and cubes

Figure 21: Example of shear failure on cylinder

Figure 22: Example of cone failure on cylinder

Figure 23: Failure on cube

.4.4 Young's modulus : data collection

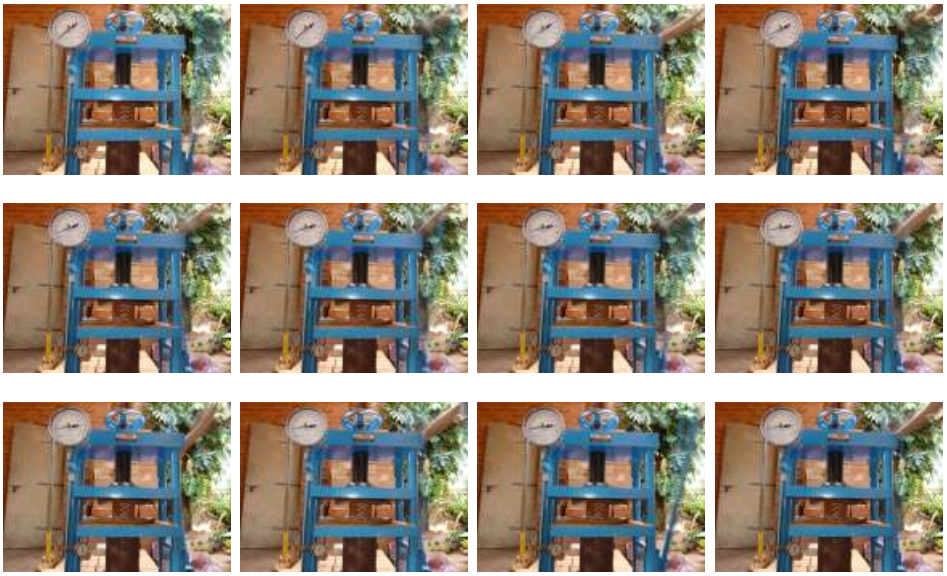


Figure 24: Data collection on multiple photographs

Figure 25: Close-up on strain and stress screens

.5 Appendix to Chapter 5

.5.1 Procedure for making walls

(a) Frameworks

(b) Mixing dry components

(c) Adding water and mixing

(d) Mixing

(e) Slump test

(f) Pouring

(g) Pouring

(h) Vibrating

(i) Leveling

(j) Leveling

(k) Leveling

(l) Unmolding

Figure 26: Building walls (1)

(a) Unmolding

(b) Close-up

Figure 27: Building walls (2)

Chapter 9

Bibliography

This bibliography covers the documentation both collected by Alberic LeHuede and Jerome Cochet during their respective internships. See Alberic's report for more details.

9.1 Books & Publications

Bâtir en terre - *AVEI Library*
An introduction to poured earth - *Michael Frerking*
Earth Manual, *U.S. DEPARTMENT OF THE INTERIOR*
Bilan CRATerre 2005-2009, *CRATerre*
Graine de Batisseur rapport 2004-2010, *CRATerre*
Dossier Béton d'argile, *Caracol*
Compte Rendu GAIA, *CRATerre*
Cohésion et comportement mécanique de la terre comme matériau de construction, *Laetitia Fontaine*
Norme NF EN 12390
ASTM C39C39M

9.2 Main Websites

www.wikipedia.org
www.earth-builder-links.com
www.earth-auroville.com
http://www.eco-caracol.com
http://www.estigc.fr/labo/beton/abrams.htm
http://webarchive.nationalarchives.gov.uk/+/http://www.berr.gov.uk/files/file15138.pdf
http://www.la.refer.org/materiaux/chapitre_six.html
http://www.vbcoa.org/resources/testcylinders.pdf