First International Conference on Bio-based Building Materials

June 22nd - 24th 2015
Clermont-Ferrand, France

INVESTIGATION OF THE MECHANICAL PERFORMANCE AND DRYING SHRINKAGE OF HEMP CONCRETE

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Abstract

The aim of this paper is to investigate the influence of the binder (lime) on the mechanical performance and drying shrinkage of hemp concrete. In order to study the mechanical behaviour, four mixes were made for: external rendering, roof insulation, floor insulation and shuttered walls. The variation of the lime was between 22 and 41 % of the global mass of the hemp concrete. Firstly, the intrinsic characteristics of the hemp shiv were measured through various tests, such as : the particle size which was determinate by scanning the particles and analysing with ImageJ, the water absorption. Secondly, the compressive strengths were determinate for all mixes at 7 and 28 days. The results show that higher compressive strengths were obtained when higher proportion of lime used. Finally the drying shrinkage of these mixes was measured in three curing conditions: the first type curing was in air with relative humidity 50% and temperature 20°C. The second type of curing was covering samples with aluminum foil with relative humidity 50% and temperature 20°C and the last type of curing was covering samples with plastic bags and to place outside with variable relative humidity and temperature. The results of drying shrinkage of hemp concrete increased when the proportion of lime reduced, and the drying shrinkage was higher for the samples kept without any cover.

Keywords: Absorption, compressive strength, drying shrinkage, hemp concrete, lime

1 INTRODUCTION

The carbon dioxide emissions are very important in the field of the construction. This one is the second sector that the most pollution after the industry. The CO_2 is responsible 50 % of creation of sere effect [Dincer 1999]. That is why, the building must integrate in its developing, the selection of building materials with a low environmental impact in order to reduce CO_2 emissions.

There is sustainable construction which it integrates three essential points, such as: the comfort, the impact on environment and the healthy. In this step, it comes to innovate some new products with low environmental impacts. Currently several steps have been implemented in order to answer to sustainable requirements such as LEED (Leadership in Energy and Environmental Design) in USA the BREEAM (BRE Environmental Assessment Method) in UK or HQE (Haute Qualité Environnementale) in France etc.

Hemp (cannabis sativa) is characterized by its environmental advantages such as its contribution to the improvement of the soil and its favourable CO_2 balance. This plant consists of the stem, the main element of this material, which contains fibers (supporting tissue) outside and hemp shiv in its center.

Hemp shiv is a vegetable aggregate; it may be mixed with the binder (lime) and water in order to create hemp concrete [Amziane 2013]. This-one is used for thirty years in France, and currently there are no regulations about the hemp concrete, hindering professionals to invest in this area. However there are some recommendations by companies such as Tradical, Chanvribloc, MNBC etc. Hemp concrete has several environmental advantages such as its contribution concerning footprint of CO_2, its low energetic consummation then of its production and its end of life without consequences for environment.

Hemp height is between 2 and 4 m and its diameter ranges from 1 to 3 cm. Its growth is relatively short about four months. The proportion of the hemp shiv is about 65 to 70% by mass, and that of the tow between 30 to 35%

The fibres are mainly used to produce pulp, or 80% of total fibre production. The rest of the fibres which represents a small percentage is used in the automotive and construction [Ademe, 2005].

It was reported that only about 5% of Europe's hemp shiv is used in the construction field, knowing that the rest is used for animal bedding [Karus 2004].

In the building, there are mainly two types of applications: The fibres that are intended for the manufacture of insulation and hemp shiv for mortar and hemp concrete. In the first case the thermal resistance can reach 0.04 to 0.06 $Wm^{-1}.K^{-1}$ [Bouloc 2006], [Kymalainen 2008].

The hemp shiv is used as aggregate for the production of lightweight concrete, initiated in 1986 in Nogent sur Seine [Bouloc 2006]. This type of aggregate is in the form of rectangular particles with average size of 2 x 0.5 x 0.2 cm^3. There are three types of hemp in function of the manufacturing process: pure hemp shiv, a hemp shiv mixed with fibres or even the entire hemp simply crushed. The density of the hemp shiv is around 110 kg/m^3 and varies depending on the state of compaction and conditions of environments [Cerezo 2005] and the air occupied 92% of its total volume.

This plant has a large aggregate capacity of water absorption through the capillary structure of the particles that compose it. It can absorb water up to four times its total mass [Sonebi et al. 2013].

To better understand the hemp concrete must initially consider the intrinsic characteristics of the hemp shiv. For this, various tests must be performed, such as the particle size can be measured through the sieve (not quite accurate) or by scanning the particles (pretty accurate, analysed with ImageJ). Then water absorption as a function of time, which plays a very important role when mixed with other components, because the hemp shiv can absorb water up to 4 times its initial mass in 48 hours, it can absorb a lot of water in only few minutes. In fact in 1 minute it absorbed around 200 % of its initial mass and the density of this vegetal aggregate is very low.

Concerning the binder, there are three fundamental points that chooses should be observed: First, the easy mixing with a specific coating of the various constituents, on the other hand, handling fresh to facilitate the implementation, and finally physical characteristics meet construction standards [Bouloc 2006].

Lime is used as the binder for the production of hemp concrete and it is manufactured by lime burning between 900°C and 1250°C (calcination), these high temperatures release carbon dioxide.

The study [Butschi 2004] reported that the compression strength on cylinders made only with lime (150 mm diameter and 300 mm height) were poor on the concrete hemp and low mechanical strength after twenty days. This suggests that this material cannot be developed with these characteristics inconclusive.

The objective of this study is to investigate the influence of the binder (lime) on the mechanical performance and drying shrinkage of hemp concrete.

2 MATERIALS, METHODES AND EXPERIMENTAL PROCEDURES

2.1 Materials

The binder used in this investigation was Tradical® PF70. It has already used in several other researches for making hemp concrete [Boutin 2005, Evrard 2008]. Tradical® PF70 is a special lime binder based on aerial lime (75%), hydraulic binder (15%) and pozzolanic binder (10%). Hemp shiv used in this study was Tradical® HF.

2.2 Methodology

Firstly, the characterisation of hemp shiv was carried out on the hemp shive aggregates in order to determine the water absorption, bulk density, and sieve test. These tests led to better understand the physical properties of the hemp shiv and to do the link with hemp concrete. Indeed hemp shiv has a large ability to absorb water, and it's bulk density is very low, and it's lower 5 times than the bulk density of lime (binder).

However, the mechanical sieve tests determined the particle size distribution of hemp shiv, indeed most of the hemp shiv particles was ranged between 1 and 6 mm (diameter), 3 and 35 mm (length). So it's very important to note the length of hemp shiv particles was between 6 and 20 times bigger than their diameter. This specificity tends to complicate the understanding of the mechanical behaviour of hemp concrete. Because the hemp shiv can be parallels or perpendiculars, it depends of the way of the casting.

Secondly, cylinder samples 11x22 cm will be tested, in order to determine the compressive strength and the modulus of elasticity of hemp concrete. Concerning these specimens the mechanical behaviour was evaluated and explained the way of crushing. In addition, there was a difference between cylinder samples and cube samples, because of their shape, in fact the repartition of the pressure is not the same.

Thirdly, some cube samples 50x50x50 mm were tested to determine the compressive strength at 7 and at 28 days.

Concerning cube samples, it was necessary to apprehend the difference between the compressive strength with parallel hemp shiv or with perpendicular hemp shiv. Finally, the drying shrinkage were measured on prisms with a size 50x50x200 mm. After the casting of specimens, it was necessary to be very careful during the measurements in order to avoid some kinds of mistakes due to the difficulty of how to fix the balls at the extremity of the samples.

On the other hand, the storage of samples was essential; in fact there was three kind of storage. The first one at relative humidity 50%, T = 20°C and without cover for the sample. The second was at relative humidity 50%, T = 20°C and with covering the sample. The last one was at relative humidity = variable, temperature = variable and the samples were covered in order to escape the evaporation of water.

2.3 Experimental procedure

Water absorption

In order to analyse the repeatability, the test was driven three times for each aggregate. The sample was homogenised to avoid fine particle segregation.

1- Dry 200g of shiv at 60°C till ±0.1 % mass variation in 24 hours is achieved
2- Put a synthetic or metallic permeable bag (with a hole around 1mm²) in water for a complete wetting.
   With ten bags we can make all tests in two days.
3- Put the bag in a "salad spinner" and turn the spinner one hundred times at approximately two rounds per second.
4- Tare the spinner bag and note the value in a data sheet.
5- Weight 25 g (M_0) of dry hemp shiv in the spinner water permeable bag (plastic or metallic bag)
6- Put the shiv bag in water during 1 min.
7- Put the bag in a " salad spinner" and turn the spinner one hundred times at approximately two rounds per second.

8- Weight the spinner shiv bag and note the value M (1 min).
9- Repeat steps 6, 7 and 8 with the same sample at different times: 15 min, 240 min (4 hours) and 2880 min (48 hours).
10- Calculate the value of absorption with the formula

$$W(t) = \frac{M(t) - M_0}{M_0} \, x \, 100$$

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Bulk density

The temperature of the test should be 21 ±2°C

1- Dry the material at 60°C until constant mass is reached (variation lower than 0.1 % between two weights at 24 hours)
2- Put hemp shiv in a sealed bag or a sealed bucket until the temperature of the room is reached.
3- Put the dried material in a glass cylinder 10 cm to 20 cm in diameter and at least twice the diameter in height. The quantity of the material has to be adjusted to be half the volume of the container.
4- Upend the glass cylinder ten times.
5- Shake to obtain a horizontal surface.
6- Use a cardboard disc and mark the level.
7- Measure the volume with water.
8- Calculate the bulk density.
9- Repeat the test 3 times (with 3 different samples of shiv)
10- Fill the table given in appendix (and in an excel sheet)

Tab. 1: Compositions in percentage of each mixes

	Mix A	Mix B	Mix C	Mix D	Mix E	Mix F
Aggregate (A)	17 %	23 %	22 %	32 %	17%	17 %
Binder (B)	36 %	31 %	41 %	22 %	42 %	53 %
Water (W)	47 %	46 %	37%	46 %	41 %	31 %
A/W mass ratio	0.36	0.50	0.59	0.70	0.41	0.54

Compressive strength protocol for cylinder 11x22 cm

1 - Weigh the specimen with mold

2 – Remove the mold with a cutter

Remove the end caps and then carefully cut off the mold taking care not to penetrate the surface of the specimen.

3 – Weigh the specimen without the mold

4 – Label the sample with the same reference as was on the mold

5 – Dry the specimen in an oven at 50°C until the mass is stable (± 0,2 %) between two weightings 24 hours apart.

6 – Store the specimen in a sealed plastic bag until the test.

7 – Measure the 3 diameters (top, bottom, and the middle) and the length of the specimen every 120° (3 measurements).

8 – No surfacing of the sample and perfect parallel plate at the starting of the test.

9 – The test must be displacement controlled at the rate of 0,05 mm/s (3 mm/min) for loading. The unloading should be (6 mm / min) or free if it is not possible to control.

10 – The rate of data acquisition should be 1 point/s

11 – Cyclic Testing:

Cycle 1: Loading from 0 to 1 % relative deformation – unloading to zero if possible (or zero displacement).

Cycle 2: Loading from 0 to 2 % relative deformation – unloading to zero if possible (or zero displacement).

Cycle 3: Loading from 0 to 3 % relative deformation – unloading to zero if possible (or zero displacement).

Final Loading: Loading from 0 to 20 % relative deformation – unloading to zero if possible (or zero displacement).

Mixing procedure

Concerning the mix procedure, there was four steps to follow:

1. Introduce hemp shiv in the recipient and turn on the mixer.
2. Add progressively the water of preparation during the mixing (2,30 min with 30 tour/ sec)
3. Add the lime and wait (30 sec, with 30 tour/ sec)
4. Add the final water in order to get hemp concrete (2 min, with 30 tour/ sec)

All these steps should be followed accurately in order to avoid some kinds of mistakes during the mixing.

3 RESULTS AND DISCUSSIONS

3.1 Sieve test

This method consisted to scan the particles of hemp shiv and use the picture in software Images Analysis in order to calculate different parameters (diameter, area etc). This method was very accurate but it took a long time to carry out the experiments. In fact, 12 scanned pictures for only 3-6 grams of hemp shiv. Three samples of hemp shiv with 4 gram and 12 pictures, per each sample were tested.

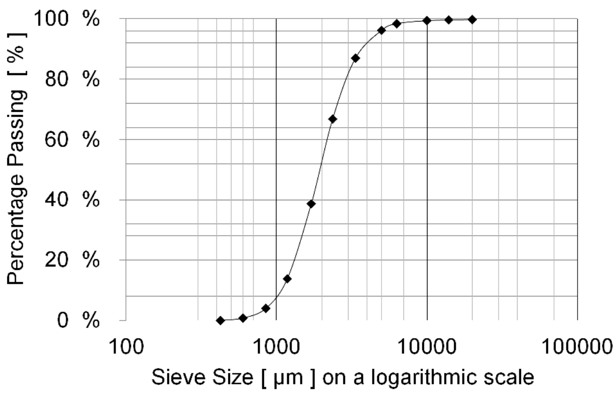

Fig 1: Sieve test of diameter of hemp shiv.

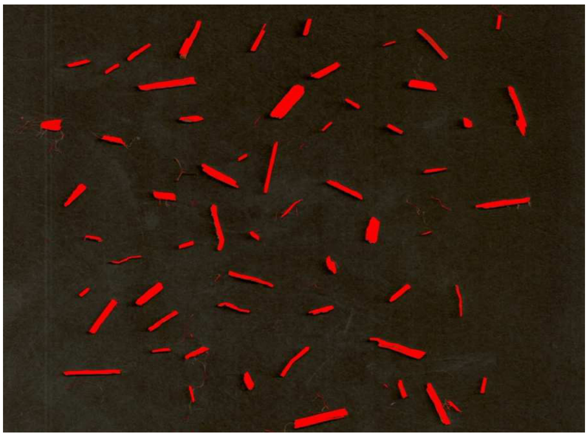

Fig 2: Analysis of hemp shiv particles with ImageJ software.

3.2 Water absorption

Figure 3 shows from the four 25g samples that were subjected to the water absorption test. It can be seen that fresh hemp shiv is able to absorb a large amount of water in a short period of time. Within 15 minutes of submersion all four samples had absorbed around 200 % of their own weight in water. At the end of the test after 4 days of submersion, the all 4 samples had absorbed around 300 % of their own weight in water.

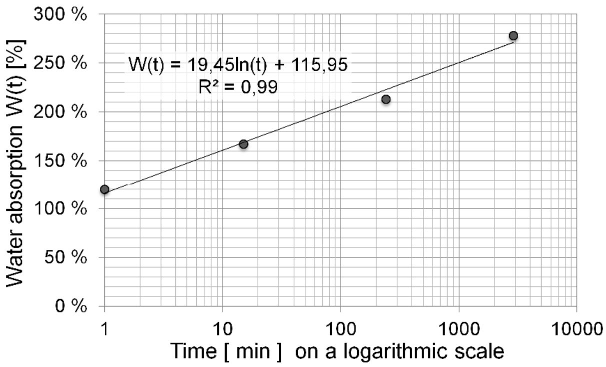

Fig 3: Water absorption test of hemp shiv.

3.3 Compressive Strength

Firstly the results of compressive strength of hemp concrete of the cylinder 22x11 cm were different compared to the cubes samples. Indeed the repartition of the pressure was constant on the cylinder and variable on the cubes. For example the transversal deformation of the sample was not similar, because theoretically the transversal deformation of the cylinder was similar everywhere whereas the transversal deformation of the cube samples was different, and this is due to the variation of radius from the centre.

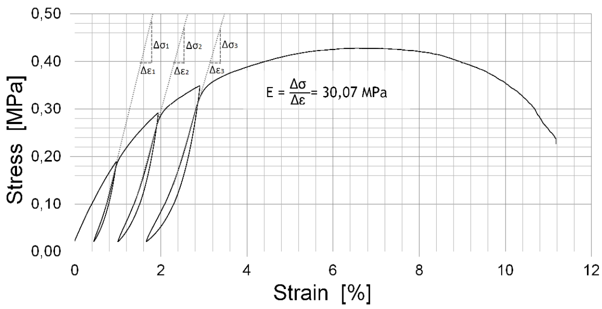

Fig 4: Young's Modulus of hemp concrete (cylinder samples 11x22 cm).

Secondly, four cylinders 11x22 cm were tested in order to evaluate the values of Young's modulus E and the resistance in compressive strength. The results obtained were: Young's modulus E= 30 MPa and f'c = 0.47 MPa for four specimens.

After the crushing, Fig. 5 shows the mechanical behaviour of these samples. Indeed there are three zones (Fig. 4): the first is between 0 and 3% of strain where there was the slope very raid and the Young's Modulus was measured, the second zone was between 3 and 9 % of strain where curve seemed to be stabilized around the maximum resistance in compressive strength around 0.47 MPa, and finally the third zone which was between 9 and 14 % of strain where the hemp concrete began losing a lot of its compressive strength so it breaks.

Concerning the behaviour during the compression (Fig. 5), the mode failure was in the middle of the sample or near the top of the sample. In fact, in the first case the bulk density of hemp concrete was approximately homogenized whereas in the second case the bulk density of hemp concrete was was lower than at the bottom and its compressive strength was lower too, that's why the failure was taking place at the top of specimen. However the compressive strength was increased when the bulk density of hemp concrete was increased.

Fig 5: Mode of failure of cylinder 11x22 cm.

The mechanical behaviour of hemp concrete depends a lot of the binder (lime), and the interactions between water and hemp shiv. As we can see in Table 1 and Fig, 6, the compressive strength of cubes 5x5x5cm was higher when the ratio Aggregate/Water ratio (A/W) was lower. The mix A had A/W ratio of 0.36, so this mix had the highest values of compressive strength compared to others mixes having A/W higher than 0.36.

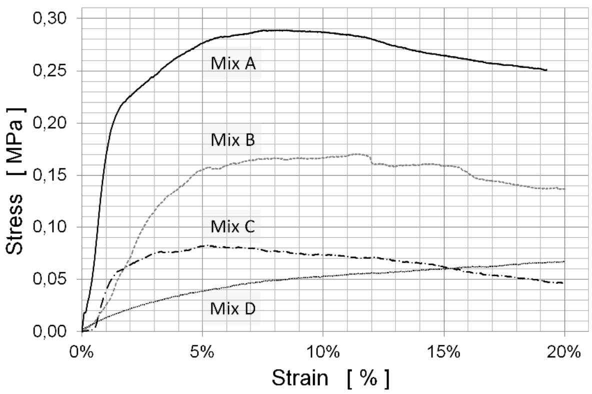

Fig 6: Compressive strength of mixes A, B, C and D.

Hemp shiv particles were parallels for all these four samples (Fig. 6). The compressive strength of these specimens would be different if hemp shiv particles would be perpendiculars and the way of the crush would be different too. So it was necessary to know that the way of the casting of hemp concrete was very important because it can influence the mechanical properties and its others physical properties such as: thermal resistance and acoustical resistance, these last one are very important for the future of this material in the construction. In fact the hemp concrete is well known for its thermal and acoustical properties more than for its resistance in compressive strength. Most of the use of the hemp concrete is destined to insulate buildings and not to support them. However there is a minimum compressive strength needed in order to support at least its-self and to have a little bit more rigidity if a render was applied.

When the hemp shiv particles were parallels to the surface of the loading applied, the mechanical behaviour was different compared to perpendicular particles (Fig. 7). Indeed the cohesion between particles was better and the loading was supported by the hemp shiv particles and the binder, that's why the deformation of theses samples after the application of loading was significantly less than in the second case. In addition, the compressive strength was higher.

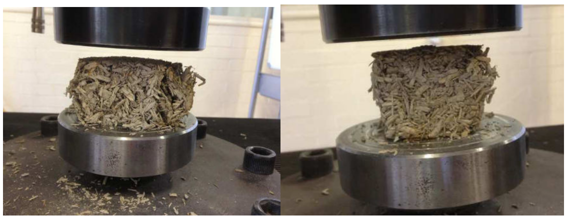

Fig 7: Mode of failure of cubes 5x5x5 cm (left side = parallel particles and right side perpendicular particles).

The interne structure of this kind of making was more stable and homogenized. The shape of the sample when the hemp shiv particle was perpendiculars is more expanded comparing to next case (parallel particles of hemp shiv). The link between particles was not assured by the binder so the deformation become bigger and bigger. Thus, the samples were more swelled, so the interne structure of these samples was less stable.

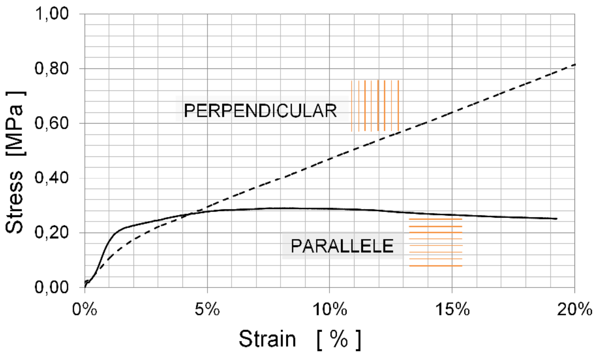

Fig 8: Mechanical behavior of hemp concrete with perpendicular and parallel orientation of particles.

The behaviour of hemp concrete when hemp shiv particles were perpendiculars of the surface of the loading applied was not stable (Fig. 8). In fact, in this case in one hand it was observed the big deformation of hemp concrete after the applied loading, this one was due certainly by the lack of cohesion between the particles (hemp shiv) and the binder. So there are only few hemp shiv particles which they were parallels to the surface of the loading applied.

On the other hand, it was observed a low a compressive strength compared to samples which had the parallel hemp shiv particles. However the cohesion between hemp shiv particles and binder can be seen well, because there was not a perturbation of the parallels hemp shiv particles. The compressive strength has no sense after 5% of strain.

3.4 Drying shrinkage

The goal of studying the drying shrinkage was to better understand the mechanical behaviour of hemp concrete and its large ability to deform (Fig. 9). In fact this kind of material has a large ability to deform thanks to its composition with its vegetal aggregate (hemp shiv particles "wood"), lime and finally water. The drying shrinkage can help to understand the problem of hydration of lime and the phenomenon of evaporation.

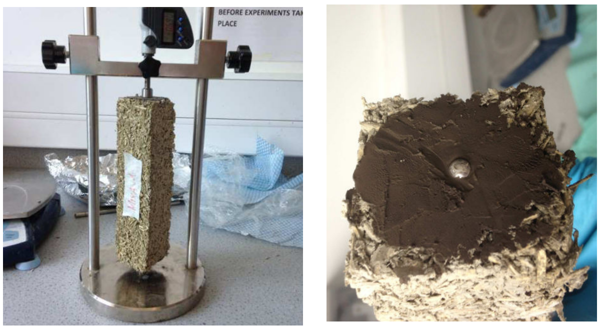

Fig 9: Measurement of drying shrinkage.

The mechanical behaviour of hemp concrete is strongly linked with the binder (lime) of hemp concrete. In fact when if there is a large proportion of lime the compressive strength of hemp concrete tend towards the compressive strength of lime, so it happened the same phenomenon with the drying shrinkage, indeed when the proportion of lime was high then the deformation of the specimen was smaller because it tends towards the mechanical characteristics of lime. It would happen the same behaviour if the proportion of vegetal aggregate varies "hemp shiv particles ", actually the mechanical features of hemp concrete would tend towards to the mechanical characteristics of hemp shiv particles.

The type of mixes plays a big role in the way of deformation of hemp concrete; indeed the drying shrinkage was smaller when the proportion of lime was higher as can be observed in Fig. 9 with different mixes.

The proportion of lime played an essential role for the drying shrinkage in fact when the amount of lime increaseed the drying shrinkage wad lower. In Fig. 11, for the mix B the evolution of mass lost and drying shrinkage had the same trend. Indeed, in this case the conditions were such as: relative humidity 50% ,T = 20°C and without cover for the sample. There were two zones of curves between 4 and 8 days, where there was a large incresae of the drying shrinkage and mass lost. The mass lost reached a level of 25% and it became constant at 10 days. So the evaporation of the water was the principal factor of this evolution. However the progression of drying shrinkage was a little bit different, in fact the increasing continued until 33 days, but it was a small variation. There were three zones concerning the drying shrinkage, the first was between 4 and 8 days (high growth), the second was between 8 and 14 days and finally the third was between 14 and 33 days.

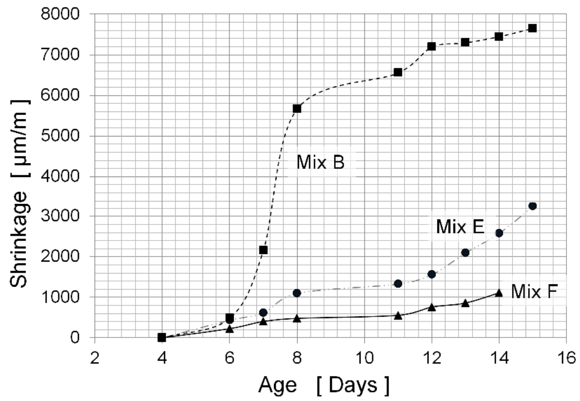

Fig 10: Drying shrinkage of mixes B, E and F.

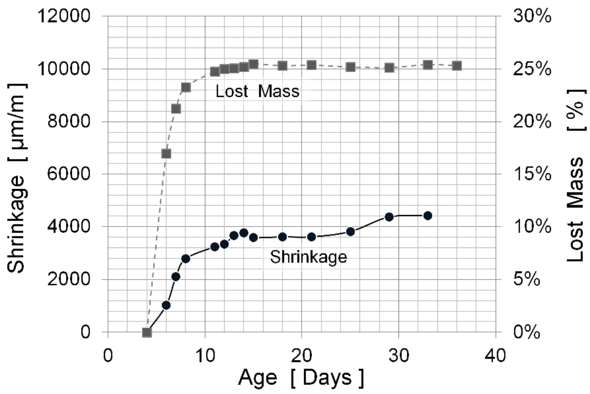

Fig 11: Drying shrinkage and mass loss of mix B with conditions (RH=50%, T= 20°C, without cover)

The mix E had 11% more of lime than the mix B and 11% less than the next mix F. Fig. 12 presents the variation of drying shrinkage and mass loss of mix E cured at relative humidity 50%,T = 20°C and without any cover. It can be observed from the drying shrinkage results of t mix E two zones: the first was between 3 and 7 days where there was a significant drying shrinkage due to the evaporation of water and the second zone where the shrinkage was increased slowly between 7 and 25 days. However the drying shrinkage values were significantly smaller than those of mix B. This can be attributed to lower W/B (W/B = 0.98 (mix E) vs. W/B =1.48 (mix B)). On the other hand, the lime became harden because the sample was cured in air, thus led to reduce the hemp shiv particles to shrink.

Regarding the mass loss, the curve of mix E was similar mix B. In fact the first zone is between 3 and 7 days, where there was a great growth of the mass loss and after there was stabilisation of the mass loss, at 25 days which reach approximately 20%. That was lower than that of mix E because of the lack of water. Indeed the principal reason of the mass loss was the evaporation of water.

With the same mix, there were different conditions of storage such as: relative humidity 50%, temperature = 20°C and the sample were protected with a cover against the evaporation of water. Concerning the drying shrinkage of mix E, there was approximately a constant slope between the age of 3 and 25 days. The shrinkage reached around 3600 µm/m and it was a slightly higher than those in Fig. 10.

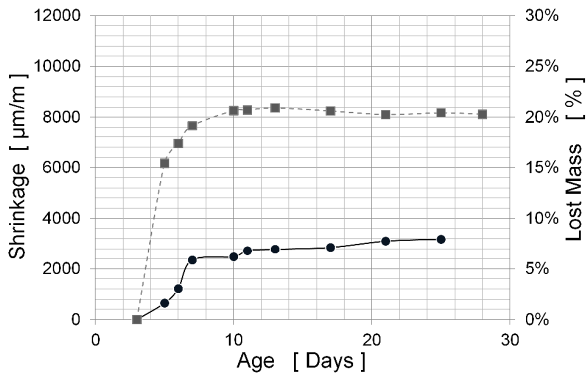

Fig 12: Shrinkage and mass loss of mix E with conditions (RH=50%, T= 20°C, without cover)

However the evolution of the slope was not the same for the sample without cover. Indeed, the fact covering the sample changes the way of evolution of drying shrinkage, because it's avoid the evaporation of water. The loss of the mass of this mix has approximately the same evolution as its shrinkage. Indeed when the samples were protected by cover against the evaporation, the loss of the mass becomes slower. The mass loss at 28 days was 16 % compared to 25% for similar mix none covered.

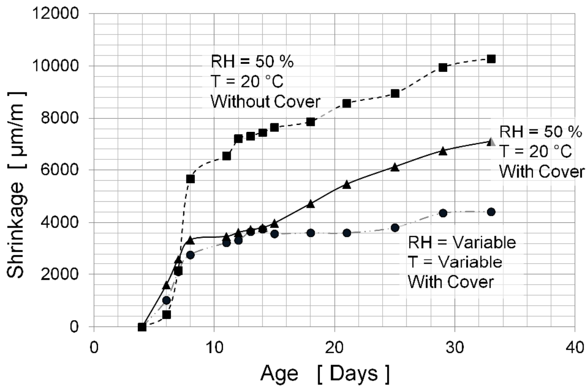

Fig 13: Shrinkage of mix B in three conditions

4 CONCLUSION

Hemp concrete has several advantageous concerning the sustainable development, thanks to its large ability to absorb CO_2 during its growth and use. That's why the field of the construction would like to integrate this healthy material the most rapidly possible, in order to reduce the CO_2 and the quantity of the use some materials which need a lot of energy at its production.

It was observed that the compressive strength of hemp concrete was very low comparing to the other materials of the construction, it has approximately 0.4 MPa, but the purpose of this material is supporting its own weight and some render.

On one hand, the variation of the proportion of the lime in the mix can influence strongly the mechanical behavior of hemp concrete. More lime led to a better compressive strength.

On other hand, it will be necessary to find equilibrium between the hemp shiv lime and water in order to get some values which will be interesting for all its physical characteristics. That is why some samples were tested for the drying shrinkage. As expected, the mass loss was very fast for the samples which were without any protective covers against the evaporation of water. The drying shrinkage of these mixes were happened quickly too, probably for the same reasons. Concerning the others samples which were covered against the evaporation of water the evolution of the lost mass and the shrinkage were different, in fact the values continued increasing slowly than the first case but some specimens have exceed the values of the first case in few days. Indeed air lime needs to have air for its hydration.

5 REFERENCES

[Ademe 2005] ADEME; Bâtiment et démarche HQE. N° 4369. November 2005.

[Amziane 2013] Amziane, S.; Arnaud, L.; Bio-aggregate-based Building Materials: Applications to Hemp Concretes. Ed. Wiley-ISTE, 2013. ISBN 9781848214040.

[Bouloc 2006] Bouloc, P.; Le chanvre industriel – productions et utilisations. Ed. France Agricole, 2006. ISBN 9782855571300

[Butschi 2004] Butschi, P.Y., Utilisation du chanvre pour la préfabrication d'éléments de construction, Congrès annuel de la Société canadienne de génie civil, Moncton, Nouveau – Brunswick, Canada 4-7 Juin 2004.

[Cerezo 2005] Cerezo, V., Popriétés mécaniques, thermique et acoustique d'un matériau à base de particules végétales: Approche expérimentale et modelisation théorique. Thèse ENTPE, 2005.

[Dincer 1999] Dincer, I., Thermal energy storage technologies: energy savings and environmental impacts, House of Technology, Budapest-Hungary, 1999.

[Karus 2004] Karus, Vogt., Industrial Applications of Natural Fibres Structure, Properties and Technical Applications, 2004.

[Kymalainen 2008] Kymalainen & Sjoberg, 2008, « Particle Boards from Papyrus Fibers as Thermal Insulation » Research Article.

[Sonebi 2013] Sonebi, M., Robinson, A., Amziane, S., "Influence of Presaturation Regime, Percentage of Lime and Compaction on the Performance of Hemp Concrete", Proceedings of First Int. Conference on Rheology and Processing of Construction Materials and 7th Int. RILEM Conf. on Self-Compacting Concrete, Paris, September 2013, CD 8p.