MULTICRITERIA ANALYSIS OF HEMP PARTICLES' IMPACT ON PHYSICAL AND THERMO-MECHANICAL PERFORMANCES OF HEMP CONCRETE

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Abstract
The hemp concrete is considered as an eco-material due to its environmental assets. Its constituents are mainly the hemp particles, binder and water to which admixtures are added eventually. The quality of hemp particles is very sensitive to the nature of soil where it is produced and also to its transformation process, which results in properties variability of hemp particles. And this may be a barrier to development of hemp concrete industry. The herein study aims to evaluate scientifically the impact of this variability on hemp concrete performances. This study is carried out through two main steps: (1) predicting the impact of hemp particles on the hemp concrete, (2) hemp concrete characterization. In the first step, a multicriteria analysis (particle size distributions, etc.) highlights the significant variability of the hemp particles and allowed to classify them into three groups. In the second step, the tests carried out on hemp concrete resulted in low, medium and high mechanical performances as predicted. A factor close to 10 is observed between the minimum and maximum compressive strengths. However, the density and the thermal conductivity are of low variability. The performed analysis show that the interaction between the hemp particles and the binder is likely to contribute to the mechanical response.
Keywords:
Variability, hemp, hemp particles, hemp concrete, mechanical properties, thermal conductivity

1 INTRODUCTION

According to the literature, the issue of the impact of hemp particles on the properties of hemp concrete has been carried out in some studies [ARN 12, NGU 10, NIY 16, STE 13]. However the analysis of these literature studies highlights the necessity and interest of an in-depth study on this subject. In fact, previous studies didn't take into account a sufficient variability of hemp particles used. In addition, during the selection procedure of hemp particles to be used, only particle size [ARN 12] and their origin [STE 13] were taken into account to distinguish them. The first step towards an in-depth study involves the implementation of a classification and selection procedure for hemp particles, taking into account several criteria. This was the main purpose of the first part of our study [NIY 15]. Within this 1st step a study was carried out to characterize and compare different types of hemp particles; characteristics considered Include among others: the bulk density, the water absorption capacity and the particle size.

Through the analysis of obtained results, it has been demonstrated that the hemp particles properties are of significant variability. For a better understanding of this observed variability, a comparative study was conducted. It is based on multicriteria analysis and has allowed to classify hemp particles in three groups. Group 1; 2 and 3 which would give good, medium and low mechanical performance of hemp concretes, respectively.

In the conclusion of that part, the next step is proposed, which consists in manufacturing hemp concrete test specimens and conducting the experimental tests in order to validate the results of hemp particles characterization. This is the main purpose of the following of the herein study and its results are presented and analyzed in this paper.

A multicriteria analysis of the results of hemp particles also allows to classify them in three groups which correspond almost to those obtained in the multicriteria classification of hemp particles. These results leads to conclusion that the hypotheses considered during the prediction of the impact of hemp particles on hemp concrete are partially verified. According to these results, low-sized hemp particles with high water absorption capacity do not necessarily result in the better performance. From this study, it is clear that only the particle size of hemp particle is not enough to predict the performance of hemp concrete. Other characteristics like water absorption capacity must be taken into account, hence, the type of hemp particles that optimizes these characteristics gives hemp concrete of high performances.

2 MATERIALS AND METHODS

In this study, at one hand we have hemp particles at the other hand hemp concrete. Materials and method used for hemp particles characterization are detailed in a previous study [NIY 15]. Among characterized hemp particles, nine have been selected for hemp concrete specimens fabrication. Specimens have been fabricated under the same conditions (formulation, curing, etc.).

2.1 Parameters for specimens' manufacturing

The wall formulation of 250 kg/m^3 has been used, cylindrical specimens 11x22cm of dimensions have been used. In order to limit the number of specimens tested, we distinguished the main test and the secondary test. In the first case, the specimens are manufactured with a great number in order to have a minimum of nine samples per age (30 and 180 days). In the second case, three control specimens per age are tested at 30 and 180 days. Insofar as 102 specimens were manufactured in the case of this study, a coding was proposed for their easy numbering (*Tab. 43*).

Tab. 43 : Coding synthesis for numbering of specimen

Type of test	Type hemp particle	Specimen size	Specimen numbering
P : Principal S : Secondary	C1 to C13	11 : Cylindrical (11x22cm)	From 1 to n in each case.

2.2 Manufacturing and testing of hemp concrete specimen

During the manufacture of specimen, for a given hemp particle, the filling of the mold has been done freely by hand with approximately four layers. To ensure the good bond of both successive layers, a scraping of the upper face is carried out. Under these conditions, a model mold is filled and weighed, then other samples are manufactured with the same mass as model sample. This trick allows indirect control of the compaction energy within the same type of hemp particles. One same person fills the model mold, to facilitate the control of compaction energy within different types of hemp particles. After manufacturing, samples are left in their molds for at least 72 hours, since the setting of hemp concrete is slow.

After demolding, there are two types of drying, namely: air drying (with the average of 21°C and 48% RH) and drying under an oven (at 60°C for 48 hours). The latter is carried out before tests of density, thermal conductivity and compressive. The method used for thermal testing is the "hot wire" method for determining the thermal conductivity. Moreover, the protocol used to perform the compressive tests as well as the method of exploitation and analysis of the stress-strain curves to determine the Young's modulus are detailed in a previous study [NIY 16]. The results obtained (density, compression strength, modulus, etc.) were exploited and analyzed using a multicriteria analysis approach. This is the same approach as that used for the classification and selection of hemp particles [NIY 15]. At the end three different groups of hemp concrete are identified. They are almost in accordance with the prediction as it is detailed in the following.

3 RESULTS AND ANALYSIS

3.1 Hemp particles characterization

The results in (*Tab. 44*) reveal high variability for each of considered characteristics. At one hand, values of bulk density ranging from 70.83 kg/m^3 to 158.85 kg/m^3 were observed. At the other hand, water absorption capacity of 112.23% to 242.59% and of 293.05 to 432.49%, are observed for initial and final values respectively. For the particle size distribution results, variabilities are also observed with for example the length of particle varies from 0.64 mm to 5.88 mm. At this stage of the study, these observed variabilities don't allow to predict the hemp particles impact on hemp concrete. Therefore, a comparative study taking into account all the characteristics at the same time is necessary and is based on a multicriteria analysis. It has been conducted and resulted in a classification of hemp particles into three groups that would give low, medium and high mechanical performance, respectively [NIY 15].

3.2 Mechanical response by type of hemp concrete

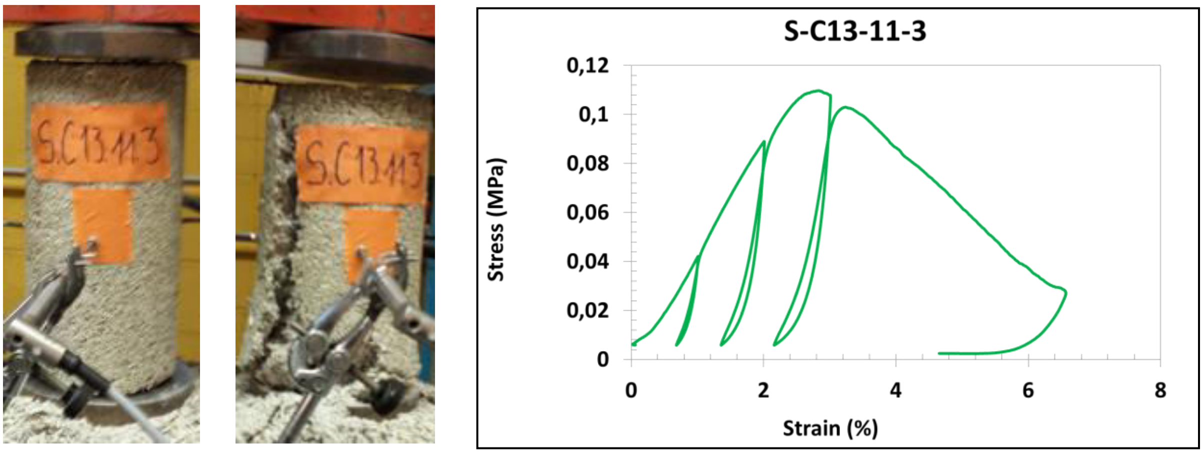
Three main hemp concrete mechanical behaviors have been observed [NIY 17], they differ in their level of strain. On one hand, a low strain around 3% has been observed (*Fig. 74*); in this case, the maximum compressive stress is observed during the third loading phase before the end of test. On the other hand, a high level of strain is observed and may reach in some cases values beyond 20% (*Fig. 77*), this last value corresponds to the maximum level chosen for the compressive test protocol [NIY 16]. Another intermediate behavior is also observed and is characterized by moderate strain level with maximum strength values around 5% of strain (*Fig. 75*).

The low level of strain is observed in the case of hemp concrete with small particle size with 1.36 mm^2 for particle mean area and a high mean specific area equal to 18822 mm^2/3g, C13. In fact, for this hemp type, the particules prevent the good connection in bonding matrix, thus weakining the whole specimen and finaly resulting in low strength. The failure mode is characterized by the total squashing of the specimen in vertical direction as shown in *Fig. 74*(b).

In the case of high strain, due to compressive loading, hemp particles rearranged themselves as a stack of layers. In fact, this rearrangement is facilitated by the particle shape, thanks to its high elongation (3.32), resulting in a good overlapping of the particles against each others. Furthermore, it is possible that the high water absorption capacity for this type of hemp (340% after 48 hours) amplifies the level of deformation. As it has been proved [DIQ 15], there is a competition of water absorption between the binder and the hemp particles.

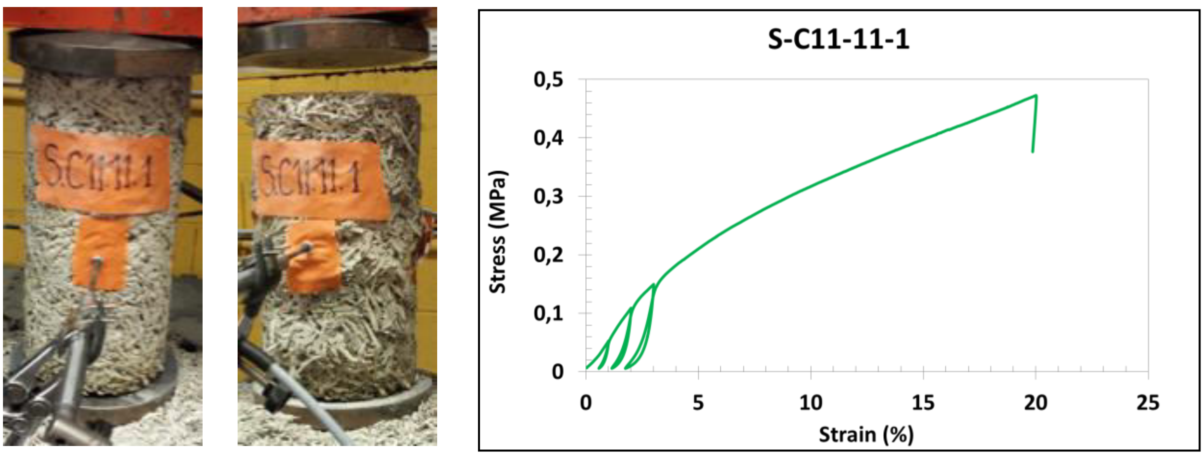
Tab. 44: Summary of results for hemp particles characterization [NIY 15].

Nomenclature	BD : Bulk Density [Kg/m3]	IWA : Initial Water Absorption [%]	FWA : Final Water Absorption [%]	MPA : Mean Particle Area [mm2]	MP : Mass of a Particle [mg]	L : Length [mm]	W : Width [mm]	El : Elongation	DF : Diameter of Feret [mm]
C1	70.83	159.83	293.05	0.91	0.18	0.64	0.19	2.62	0.32
C2	89.74	194.15	379.22	4.89	0.84	3.40	1.04	3.47	1.79
C3	118.03	242.59	432.49	1.57	0.28	1.11	0.32	2.63	0.58
C4	118.27	233.79	358.33	1.94	0.35	1.45	0.44	2.60	0.76
C5	125.66	153.99	351.28	8.10	1.77	5.88	1.40	4.97	2.78
C6	128.20	181.39	358.53	5.31	1.14	4.20	1.27	3.95	2.23
C7	129.91	163.59	321.94	3.25	0.79	1.93	0.42	3.19	0.84
C8	143.55	152.73	328.04	6.96	1.51	5.59	1.23	5.52	2.53
C9	147.50	211.77	381.47	6.95	1.50	5.11	1.38	4.47	2.58
C10	130.65	112.23	307.31	0.82	0.15	0.77	0.25	2.28	0.41
C11	95.40	165.85	344.58	1.72	0.23	1.46	0.34	3.32	0.66
C12	103.93	162.89	338.70	1.18	0.18	1.02	0.28	2.77	0.50
C13	158.85	226.16	375.06	1.36	0.22	1.11	0.52	2.27	0.80
Minimum	**70.83**	**112.23**	**293.05**	**0.82**	**0.15**	**0.64**	**0.19**	**2.27**	**0.32**
Maximum	**158.85**	**242.59**	**432.49**	**8.10**	**1.77**	**5.88**	**1.40**	**5.52**	**2.78**
Average	**120.04**	**181.61**	**351.54**	**3.46**	**0.70**	**2.59**	**0.70**	**3.39**	**1.29**
SD	**24.72**	**37.97**	**36.38**	**2.64**	**0.60**	**1.96**	**0.48**	**1.05**	**0.94**



(a) (b) (c)

Fig. 74: mechanical response: low deformation, specimen before (a) and after (b) test with stress-strain curve (c) [NIY 17].



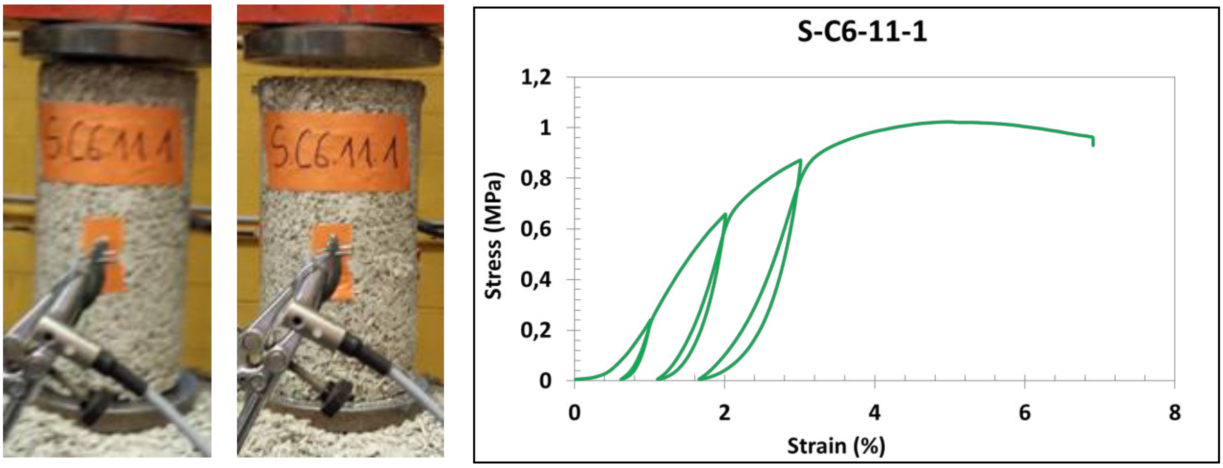
(a) (b) (c)

Fig. 75: mechanical response: high deformation, specimen before (a) and after (b) test with stress-strain curve (c) [NIY 17].

Since this hemp particle has a high water absorption capacity, the water required for the setting and the hardening process of the binder is absorbed by hemp particles; probably the false setting phenomenon occurs. Then the binder does no longer fulfill its mechanical role, and load is transmitted to hemp particles. As a result, the observed mechanical behavior is similar to that of hemp particles under compression as illustrated in *Fig. 75* (b) and *Fig. 76* (b) for hemp particles and concrete, respectively. It should be noted that these findings are not necessarily generalizable for all the analyzed nine hemp particles types. This let us assume that the chemical interaction between the binder and the hemp particles used can also contribute to the observed mechanical response. The study of the chemical composition and molecules in plant cell surface may help to better understand the impact of the chemical interaction hemp particles/binder on the setting and hardening process of hemp concrete material. In previous studies [DIQ 15], [DIQ 16], it was shown that these chemical compounds « extracts » may affect significantly the setting process for hydraulic binders.

(a) (b)

Fig. 76: hemp particles mechanical response, before (a) and after (b) compression test [GOU 14].



(a) (b) (c)

Fig. 77: mechanical response: medium deformation, specimen before (a) and after (b) test with stress-strain curve (c) [NIY 17].

3.3 Multicriteria analysis for hemp concrete properties

The multicriteria analysis allowed to classify and to select the different types of hemp particles with the possibility to predict their impact on hemp concrete properties [NIYI 15]. As conclusion to this step of the study, it was suggested to conduct an experimental study on hemp concrete in order to validate the proposed classification. This involves the validation of assumptions taken into account during the analysis. The results obtained show significant variability (*Tab. 45*). From these results, a correlation study between hemp concrete properties revealed very good correlation's coefficient for some properties. In addition, a separate analysis of hemp concrete properties one by one or two by two allow to evidence the first trend on the impact of hemp particles to hemp concrete. At this level, it is possible to assess the quality of hemp concrete by taking into account not more than two characteristics at a time. As these results are inconclusive, a comparative study taking into account several characteristics at the same time is necessary. It allows to highlight the impact of hemp particles on hemp concrete. The methodology used is the same as for hemp particles [NIY 15].

3.4 Classification of different types of hemp concrete

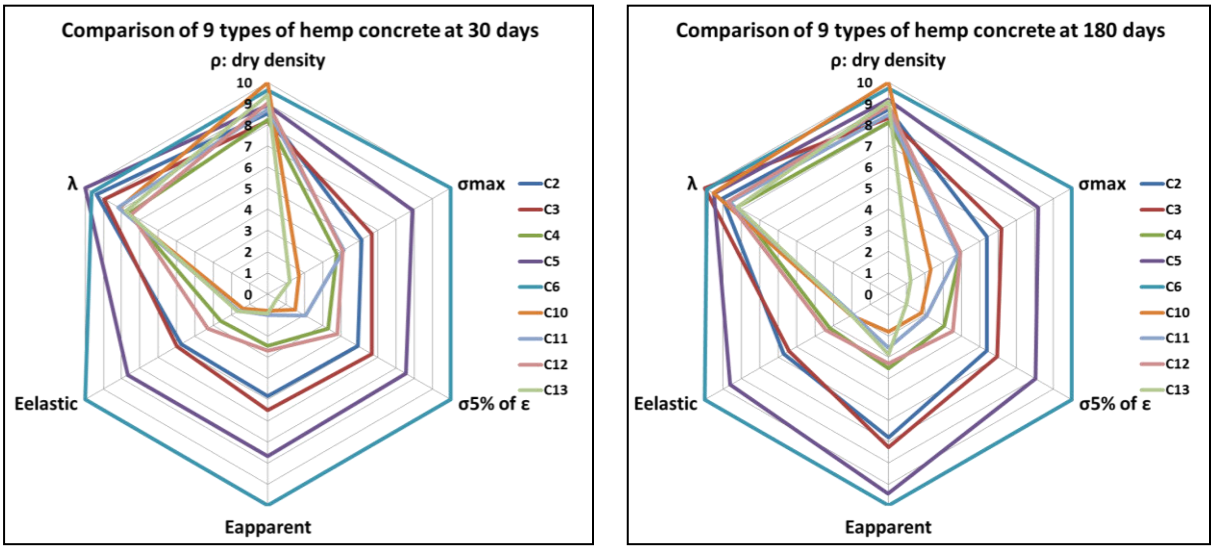
As a reminder, thirteen different types of hemp particles have been characterized (*Tab. 44*) and have been subjected to a multicriteria study for their classification [NIY 15]. Subsequently, nine types among them were selected and used for the manufacturing of hemp concrete specimens. During the selection procedure, three identified groups have been taken into account so that each of them was represented. The selection is detailed below:

- group 1: C10, C12 and C13;
- group 2: C2, C3, C4 and C11;
- group 3: C5 and C6.

Analysis of the study demonstrates the sensitivity of hemp concrete properties due to the hemp particles used. Some are less impacted by the type of hemp, while others are largely modified. On the same scale of comparison as in [NIY 15], the results of (*Fig. 78*) show dispersions ranging from 1 to 10, especially for mechanical performances. It is also observed dispersions ranging from 8 to 10 for dry density and thermal conductivity properties. For the latter, obtained values for different hemp conretes are closer to each others. This confirms and justifies the choice made during the classification procedure [NIY 15], which consists in basing the prediction approach on the mechaical performances, as they are in fact the most impacted by hemp particles type. Beyond the graphical representation in *Fig. 78*, it is important to conduct an in-depth analysis in order to understand the links between dispersion of hemp concrete properties and hemp particles. A separate representation allows to better distinguish the hemp concrete located in the center, the middle and the periphery of radar diagram, one can therefore differenciate cleary the three groups

Tab. 45: Mean values for different properties of hemp concrete at 30 and 180 days

N° of specimen/ Age	Dry density (ρ) [kg/m^3]		Maximum strength (σ) [MPa]		Strength (σ) at 5% strain (ε) [MPa]		Apparent modulus (E) [MPa]		Elastic modulus (E) [MPa]		Thermal conductivity (λ) [W/m.K]	
	30d	**180d**	**30d**	**180d**	**30d**	**180d**	**30d**	**180d**	**30d**	**180d**	**30d**	**180d**
P-C2-11	407.50	429.58	0.55	0.57	0.51	0.55	29.49	29.09	54.22	58.84	0.116	0.083
P-C4-11	392.74	399.43	0.40	0.42	0.34	0.31	15.00	15.09	29.45	33.12	0.094	0.075
P-C5-11	426.09	452.33	0.84	0.87	0.79	0.82	46.77	40.42	87.41	88.97	0.124	0.087
P-C12-11	431.02	437.93	0.44	0.42	0.40	0.36	16.39	14.12	37.66	35.22	0.093	0.080
S-C3-11	389.90	410.04	0.61	0.66	0.60	0.61	33.49	30.99	56.81	55.98	0.111	0.092
S-C6-11	460.25	479.67	1.07	1.07	1.05	1.02	61.00	42.79	114.17	103.44	0.119	0.091
S-C10-11	477.65	493.48	0.18	0.25	0.16	0.18	4.89	7.68	15.59	20.94	0.101	0.087
S-C11-11	416.71	417.55	0.44	0.40	0.22	0.21	6.17	10.91	18.45	20.08	0.101	0.079
S-C13-11	449.19	449.25	0.13	0.13	0.05	0.10	5.68	12.27	18.99	20.72	0.096	0.075



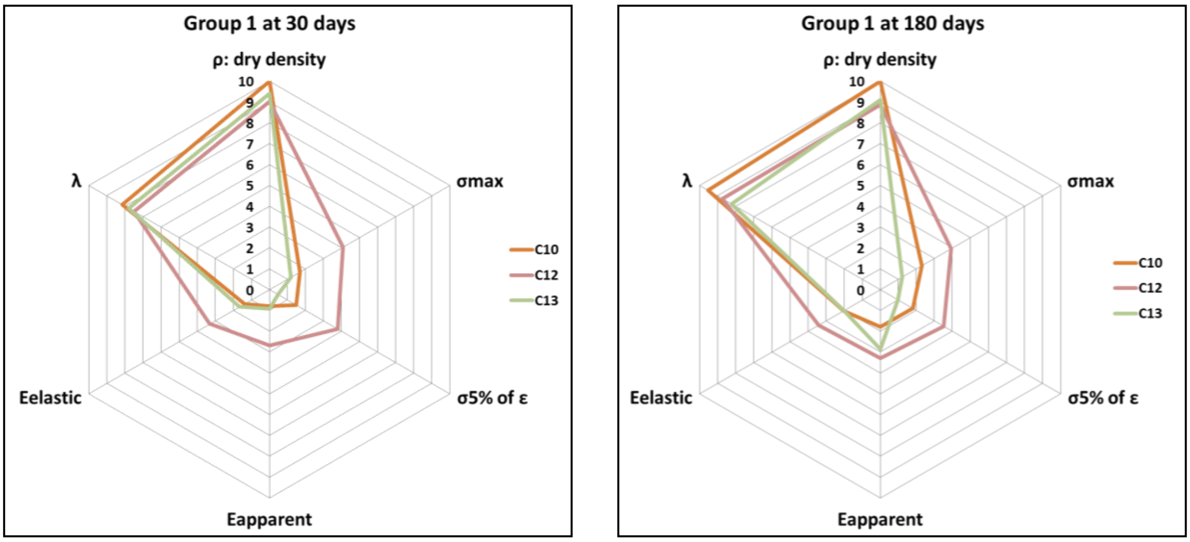
(a) (b)

Fig. 78: comparison of hemp concretes taking into account different characteristics, (a) 30 days and (b) 180 days.

3.3.1 Hemp concrete of group 1

The hemp concrete of this group are those manufactured with hemp particles which have been classified in group 1. Indeed, hemp particles in this group are characterized by small particles size with also low and medium water absorption capacity [NIY 15]. According to considered assumption, since those properties were deemed to be detrimental to mechanical performance, and given their low values, it was concluded that these hemp particles would result in hemp concrete with high mechanical performances.

In opposite to prediction, obtained hemp concretes are of low mechanical performances. In fact, the water absorption capacity considered as harmful is not necessary detrimental in reality. The beneficial or harmful character is probably related to the nature of binder used. In a study by Nguyen [NGU 10] four types of binder were used, those containing pouzzolans in addition, resulted in better mechanical performances while cement-based hydraulic binders leaded to low mechanical performances.



(a) (b)

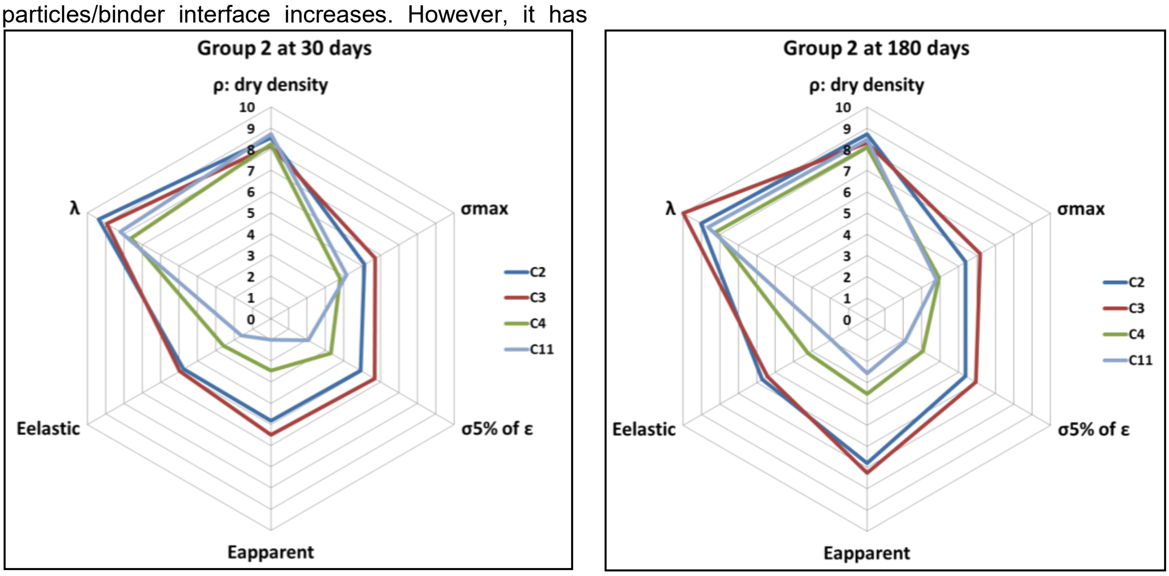
Fig. 79: hemp concretes classified in group 1

Morever, the study by Arnaud and Gourlay [ARN 12] concluded that the reduction in particle size improves the mechanical performance of the hemp concrete. However, this is not the case from the results of herein study. This finding was also highlighted in the work of Stevulova et al. [STE 13]. According to their results, the reduction in the particle size leads to an improvement of mechanical performance of hemp concrete at one condition that the used hemp particles are of the same origin. It is to note that, while using the Tradical PF70 binder, Nguyen [NGU 10] also found an improvement of mechanical performance when the particle size increases. From our results, it is demonstrated that the higher the specific surface area, the lower the mechanical performance. This finding is partially in agreement with the results of Arnaud and Gourlay [ARN 12], because the more the specific surface area increases, the more the hemp particles/binder interface increases. However, it has been demonstrated by Nozahic [NOZ 12] that this interface which is bad by nature contributes to poor hemp concrete mechanical performance.

Thus, it is clear that the beneficial or detrimental character of the particle size and the water absorption capacity depends on the type of binder and its interaction with hemp particles.

3.3.2 Hemp concrete of group 2

In this group, hemp concrete are characterized by an improvement of their mechanical performances compared to those of group 1. The difference observed for the mechanical performances of this group leads to two subgroups: group A composed of C2 and C3 with subgroup B composed of C4 and C11. The latter seems to belong to group 1 [NIY 15]. These subgroups are the result of hemp particles characteristics as explained below.



(a) (b)

Fig. 80: hemp concretes classified in group 2

On the one hand, it should be noted that hemp concrete C11 can pass from group 1 to group 2; on the other hand, the C12 classified in group 1 can also pass to group 2 [NIY 15]. Indeed, when classifying these hemp particles [NIY 15], their positions on the radar diagram could lead to classify them in group 1 or 2. Then, the analysis of their geometric characteristics allowed to decide. C11 is characterized by a higher geometry than C12, that the reason why it has been classified in group 2.

On the other hand, in the same subgroup, according to the results of classification [NIY 15], the C4 is located at the boundary between the two groups 1 and 2. Its slightly larger size and relatively low water absorption capacity compared to group 1 hemp particles characteristics, allowed to classify it in group 2.

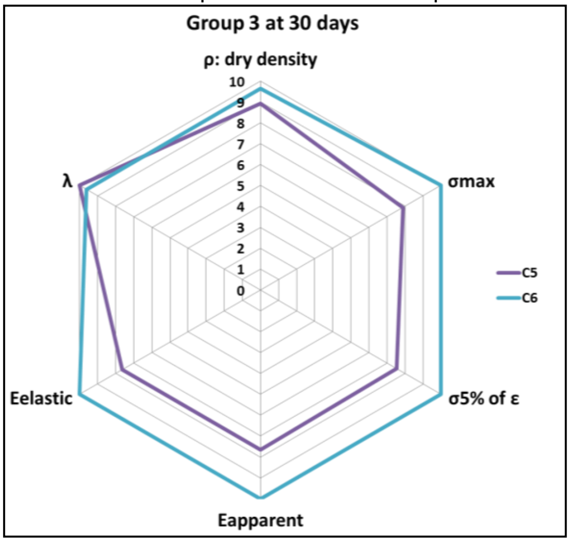
While hemp particles of group 1 have mechanical performance values ranging from 1 to 4 on the same comparison scale, one can observe the improvement in group 2, with values ranging from 4 to 7, in particular for the maximum compressive strength.

3.3.3 Hemp concrete of group 3

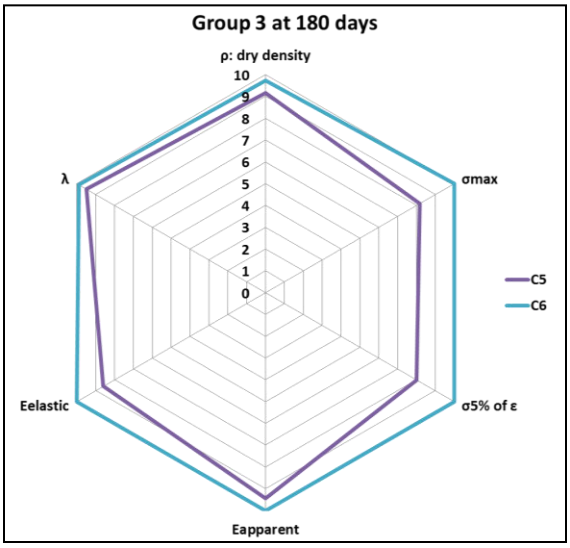
Hemp concrete of this group are obtained from hemp particles that were also located at the periphery of the radar diagram. According to our hypothesis, these hemp particles were supposed to results in hemp concrete with poor mechanical performances. Nevertheless, a reservation had been expressed about hemp particles of this group due to a better correlation between the results of their characteristics. This was not the case for hemp particles of group 1 and 2 [NIY 15].

Understanding the underlying causes of this good correlation between these characteristics can help to better understand why these hemp particles give high mechanical performance compared to others. Among tracks that can be exploited is the analysis of the internal structure at the microscopic scale for these hemp particles. This will allow to better understand their porosities and to make the link between the hemp particle size and the water absorption capacity.

Compared to other groups (1 and 2), these hemp concretes have higher mechanical performances of the order of 8 to 10 always on the same scale of comparison.



(a)



(b)

Fig. 81: hemp concretes classified in group 3

4 CONCLUSION

Type of used hemp particle has been identified as the source of significant dispersions observed, in particular in the case of mechanical performance. It has been highlighted the three main mechanical response during the compression test on hemp concrete. These are mainly mechanical behaviors characterized by low, medium and high level of deformation. The large specific surface area of hemp particles was identified as the source of weak binding of binder-hemp particles interface, resulting in total crushing of specimen. Moreover, the high water absorption capacity which is probably the cause of “false setting effect” associated with particle size have been identified as the source of high level of deformation observed. Unlike the literature, it is clear that only hemp particle size is not enough to predict the performances of hemp concrete produced. Therefore, other characteristics (water absorption, etc.) must be taken into account. Thus, the hemp particle that optimizes these characteristics will result in a hemp concrete with better performances. However, it is possible that by changing the type of binder, the mechanical response may change also.

5 ACKNOWLEDGMENTS

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