

Chapter 2

Investigating Hemp Concrete Mechanical Properties Variability Due to Hemp Particles

César Niyigena, Sofiane Amziane, and Alaa Chateauneuf

Abstract Nowadays, the use of bio-source and recyclable materials are experiencing considerable success. They include among others, the wood, the bamboos and the innovative concrete in which vegetable origin aggregates are used. In this latter case, several types of aggregates are used like sunflower, hemp particles, etc. Hemp particles are increasingly used thanks to its environmental asset, such as the positive CO₂ balance and its easiness lifecycle management. In construction applications, they have also other advantages like good thermal and acoustic insulation properties. However, its major drawback is related to low mechanical performance. The present work investigates the impact of hemp aggregates on the mechanical properties of hemp concrete. Nine different hemp particles from different origins (country, region, etc.) with varied properties (size, water absorption, etc.) are used in the same conditions (binder, specimen fabrication, etc.). Fabricated specimens were submitted to mechanical compression test, then compressive strength and moduli are analysed. The obtained results show high variability. Hemp particles impact results in a mechanical response with low, medium and high levels of deformation. A factor close to 10 is observed between the minimum and maximum compressive strengths. The performed analyses show that the interaction between the hemp particles and the binder is likely to contribute to the mechanical response. Hence, further investigations taking into account their chemical composition may allow to better understand this interaction impact.

Keywords Hemp particles • Mechanical properties • Variability • Hemp concrete

2.1 Introduction

The impact of hemp particles on hemp concrete have been treated in some different studies [1–3]. In those studies, the used hemp are of limited variability. Moreover, the considered properties in those studies are mainly based on particle size and hemp origin [1, 2]. Within those studies, since many parameters are taken into account at the same time, such as the humidity, the binder type, the curing conditions [1], the specimen size [3], etc. then it comes difficult to assess the real impact of hemp particles due to parameter interferences.

This study focuses on the variability of hemp concrete due to hemp particles. The selection procedure for nine hemp particles has been developed in a previous study [4] in which many different characteristics are taken into account such as: the water absorption capacity, the hemp particles size including the specific area, the width and length of particles, its mass and also the density. Beyond the selection, the main aim is to predict the impact of selected hemp particles on hemp concrete mechanical performance. The outcome of this research revealed three categories of hemp particles: category 1 is supposed to result in high mechanical performance, the category 2 in medium performance and the category 3 in low mechanical performance. In this study, it is recommended to conduct laboratory testing in order to validate the predicted results. The main aim of the herein study is to analyse the obtained results. As it will be presented so far, the obtained results are characterized by three main mechanical response behaviors with compressive strengths ranging from 0.11 to 1.10 MPa.

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2.2 Materials and Method

Cylindrical specimens of 11 cm in diameter and 22 cm of height were used with nine hemp particles and the same commercial hydraulic binder. The characterization results for bulk density, water absorption and particle size distribution, are detailed in the previous study [4]. The protocols and methods related to manufacturing, mixing process are given in Sect. 2.2. The compressive strength tests have been made using Zwick machine under the same protocol detailed in [3], and the experimental results were collected for variability analysis. The considered mechanical properties are compressive strength and moduli (apparent and elastic); in this later case, the protocol for calculation is detailed in [3].

2.2.1 Hemp Shiv Characterization

The used hemp particles have been characterized in [4], where the main properties considered for their characterization are mainly: the bulk density, the particle size and the water absorption capacity. The main results are given in Table 2.1. Among these 13 characterized hemp particles, based on the recommendations in [4], only 9 have been selected to fabricate specimens of the herein study. They are underlined in the Table 2.1.

2.2.2 Preparation of Compression Specimen

2.2.2.1 Mix Proportioning

In construction, hemp concrete has several applications, such as: filling wooden frame walls, roofing insulation, etc. To each application, corresponds a given number of specifications such as minimum compressive strength and Young's modulus [5], which can be met by specific formulations. For the purpose of the herein study, it has been decided to use a unique formulation corresponding to wall application [5], as the objective is to analyze the effect of hemp particles rather than formulation itself, any other one may have been used. The quantities in kilograms per batch of 100 L are detailed in Table 2.2; these quantities are calculated by taking into account a mean bulk density for hemp particles equal to 120 kg/m³.

Table 2.1 Characterization results of different used hemp particles [4]

Nomenclature	Bulk density (kg/m ³)	Initial water absorption (%)	Final water absorption (%)	Particle mean area (mm ²)	Particle mass (mg)	Particle mean length (mm)	Particle mean width (mm)	Particle elongation	Particle equivalent diameter (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	3.4	1.04	3.47	1.79
<u>C3</u>	<u>118.03</u>	<u>242.59</u>	<u>432.49</u>	<u>1.57</u>	<u>0.28</u>	<u>1.11</u>	<u>0.32</u>	<u>2.63</u>	<u>0.58</u>
<u>C4</u>	<u>118.27</u>	<u>233.79</u>	<u>358.33</u>	<u>1.94</u>	<u>0.35</u>	<u>1.45</u>	<u>0.44</u>	<u>2.6</u>	<u>0.76</u>
<u>C5</u>	<u>125.66</u>	<u>153.99</u>	<u>351.28</u>	<u>8.1</u>	<u>1.77</u>	<u>5.88</u>	<u>1.4</u>	<u>4.97</u>	<u>2.78</u>
<u>C6</u>	<u>128.2</u>	<u>181.39</u>	<u>358.53</u>	<u>5.31</u>	<u>1.14</u>	<u>4.2</u>	<u>1.27</u>	<u>3.95</u>	<u>2.23</u>
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	147.5	211.77	381.47	6.95	1.5	5.11	1.38	4.47	2.58
<u>C10</u>	<u>130.65</u>	<u>112.23</u>	<u>307.31</u>	<u>0.82</u>	<u>0.15</u>	<u>0.77</u>	<u>0.25</u>	<u>2.28</u>	<u>0.41</u>
<u>C11</u>	<u>95.4</u>	<u>165.85</u>	<u>344.58</u>	<u>1.72</u>	<u>0.23</u>	<u>1.46</u>	<u>0.34</u>	<u>3.32</u>	<u>0.66</u>
C12	103.93	162.89	338.7	1.18	0.18	1.02	0.28	2.77	0.5
<u>C13</u>	<u>158.85</u>	<u>226.16</u>	<u>375.06</u>	<u>1.36</u>	<u>0.22</u>	<u>1.11</u>	<u>0.52</u>	<u>2.27</u>	<u>0.8</u>
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	8.1	1.77	5.88	1.4	5.52	2.78
Mean	120.04	181.61	351.54	3.46	0.7	2.59	0.7	3.39	1.29
Standard deviation	24.72	37.97	36.38	2.64	0.6	1.96	0.48	1.05	0.94

Table 2.2 Tested formula for wall application per batch

Shiv (kg)	Binder (kg)	Water (kg)	Ratio water/binder	Ratio shiv/binder
11.4	23.75	28.5	1.2	0.48

Fig. 2.1 Different mixer type,
(a) for classic concrete and
(b) specific for hemp concrete



2.2.2.2 Mixing of Hemp Concrete

The hemp aggregates are put in the mixer with prewetting water equal to a quarter of total amount of necessary water. After few minutes of mixing, the second quarter of water is added with the binder. The mixing is maintained, then depending on the homogeneity of the mixture the third and last quarter of water are added and keep mixing until the perfect mixture homogeneity is obtained. For a good homogeneity, it is better to use a suitable mixer; a specific one for hemp concrete is shown in Fig. 2.1b below.

In fact, on one hand, the conventional mixer has primary and secondary blades both fixed on vertical rotating axes (Fig. 2.1a). Only the axis for primary blades is motorised and allow the mixing. During the mixing process the secondary blades are then entrained by the concrete mixture in opposite direction to primary blades. This rotation in both direction allows a good homogeneity for the mixture. In the case of hemp concrete, as it is lightweight, it becomes difficult to induce secondary blades rotation. In opposite, the hemp concrete is stuck inside the blades thus forming a kind of bloc which rotates in the mixer without mixing the constituents properly, which makes this conventional mixer unsuitable for hemp concrete.

On the other hand, a mixer with horizontal rotating axis with blades ramified to it, is well adapted for hemp concrete (Fig. 2.1b). As all blades are connected to the horizontal motorized axis and their possible rotation in both directions, it becomes more easier and practical to properly mix the hemp concrete.

2.2.2.3 Numbering of Fabricated Specimens

According to the recommendations in [4] for a given hemp particles type, 3 or 9 specimens are fabricated for each type of the 9 selected hemp particles. To identify hemp particles: 9 specimens are considered for “primary test” (C2, C4, C5 and C12), and 3 specimens are considered for “secondary test” (C3, C6, C10, C11 and C13). Therefore the numbering of specimens is as following: P and S for primary and secondary tests, respectively, 11 stands for the size of specimen 11×22 cm, Ci represents a given hemp particles type and n is the number of the specimen. For example, “P-C2-11-3” stands for primary test from hemp particles C2, size 11×22 cm specimen number 3.

2.3 Results and Discussion

2.3.1 Mechanical Response

Three main hemp concrete mechanical behaviors have been observed, they differ in their level of strain. On one hand, a low strain around 3 % has been observed (Fig. 2.2); 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 deformation is observed and may reach in some cases values beyond 20 % (Fig. 2.5), this last value corresponds to the maximum level chosen for the compressive test protocol [3]. Another intermediate behavior is also observed and is characterized by moderate levels with maximum strength values around 5 % of strain (Fig. 2.3).

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 $18,822 \text{ mm}^2/\text{g}$, C13. In fact, for this hemp type, the particles prevent the good

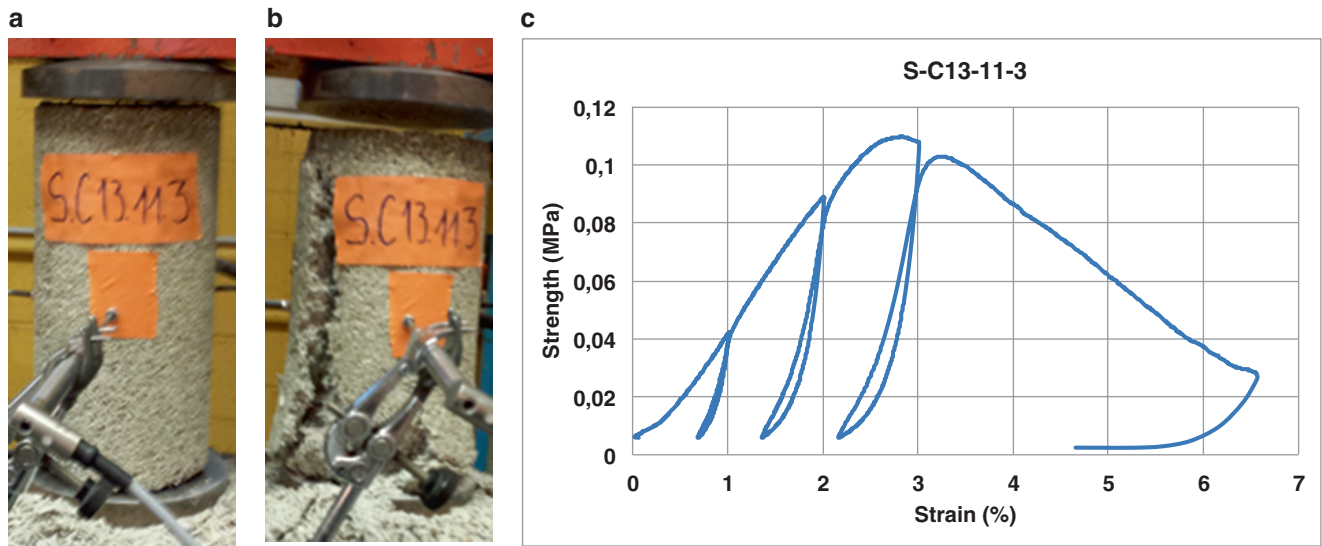


Fig. 2.2 Mechanical response: low deformation, specimen before (a) and after (b) test with strength-strain curve (c)

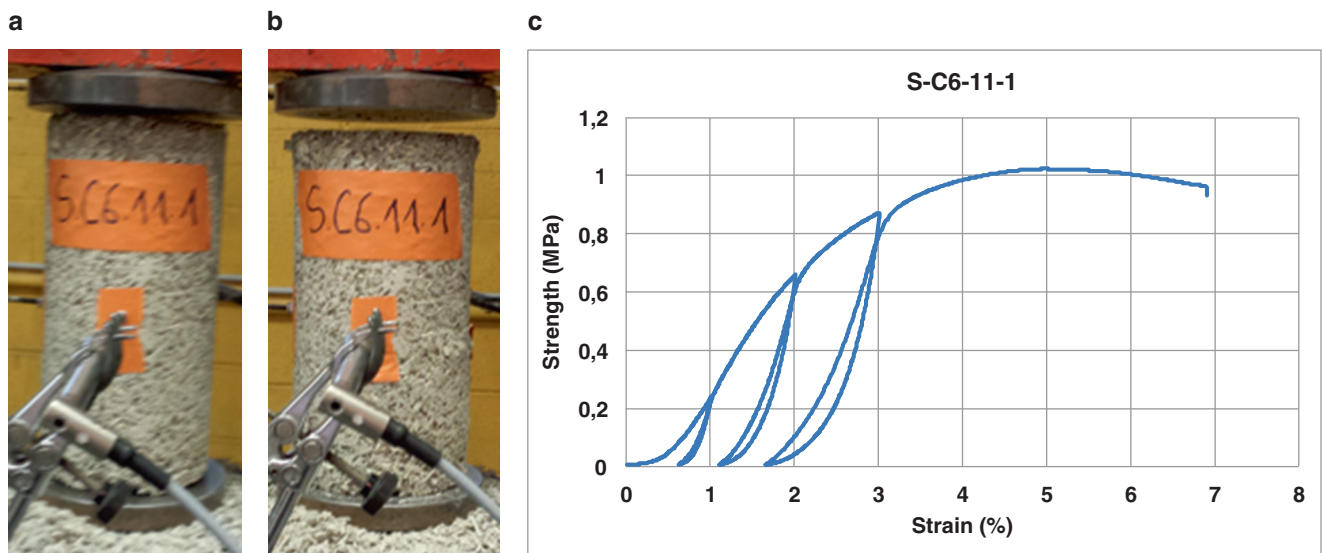


Fig. 2.3 Mechanical response with medium deformation, specimen before (a) and after (b) test with strength-strain curve (c)

Fig. 2.4 Hemp particles mechanical response, before (a) and after (b) compression test [8]

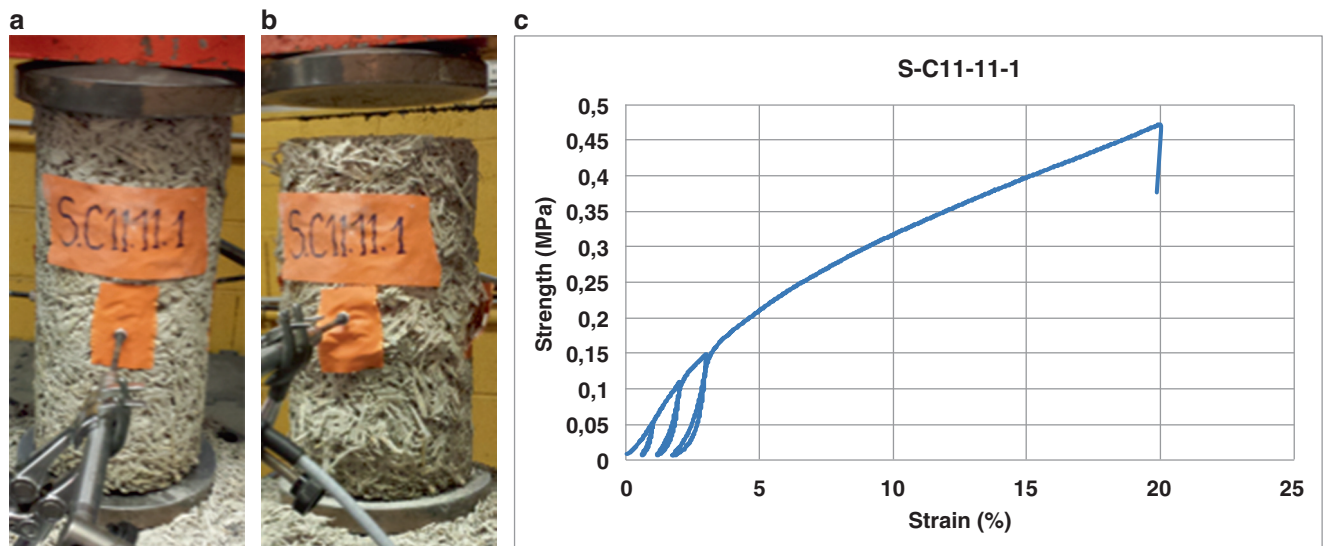
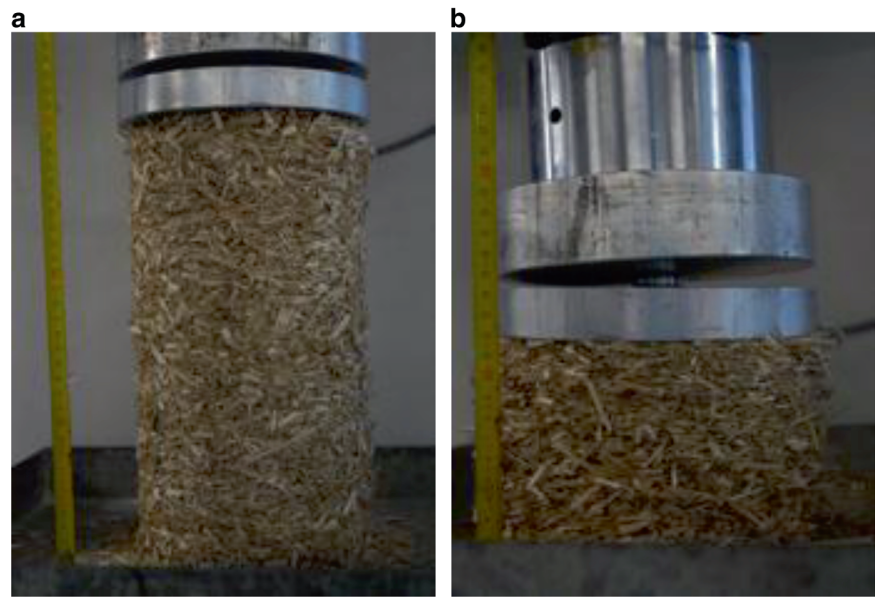


Fig. 2.5 Mechanical response with low deformation, specimen before (a) and after (b) test with strength-strain curve (c)

connection in bonding matrix, thus weakening the whole material (specimen) and finally resulting in low strength. The failure mode is characterized by the total squashing of the specimen in vertical direction as shown in Fig. 2.2b.

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 h) amplifies the level of deformation. As it has been proved [6], there is a competition of water absorption between the binder and the hemp particles. Since this hemp shiv 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 Figs. 2.4b and 2.5b for hemp particles and concrete, respectively. It should be noted that these findings are not necessarily generalizable for all the analysed 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 [6, 7], it was shown that these chemical compounds “extracts” may affect significantly the setting process for hydraulic binders.

2.3.2 Hemp Particles Impact on the Mechanical Performance

The previous section illustrates how the mechanical response differs depending on hemp particles. At this stage, only the main behaviors have been discussed. This section, focus on the obtained results for all the nine hemp particles. The main considered properties are the compressive strength and the modulus.

2.3.2.1 Compression Strength

The compressive strength results show considerable dispersion at two levels. On one hand, we observe the variability related to used hemp particles with a factor equal to 10 between the minimum and maximum strengths, particularly between hemp particles C13 and C6, respectively (Fig. 2.6). On the other hand, we also observed the significant dispersion within a given type of hemp particle. For example, we have a minimum of 0.47 MPa and 0.65 MPa with a maximum of 0.65 MPa and 0.99 MPa for hemp C2 and C5, respectively (Fig. 2.6). This intrinsic variability of the material shows to what extend the number of samples considered may impact the result, hence it is necessary to take enough samples for statistical significance of results. To our knowledge, there is no specific study for this issue in the case of hemp concrete. In the herein study 9 and 3 samples were used for primary and secondary tests, respectively. The obtained results are presented in the current section, the analysis is proposed later in Sect. 3.3.

2.3.2.2 Elastic Modulus

The observed dispersions for compressive strength are also confirmed in the case of the elastic modulus, although we observe low dispersion for C2 hemp concrete. These results highlight also the sensitivity of the variability with respect to the relevant property and of course its measurement method. In [3], the low variability were observed for density, while compressive strength and elastic modulus had high variabilities.

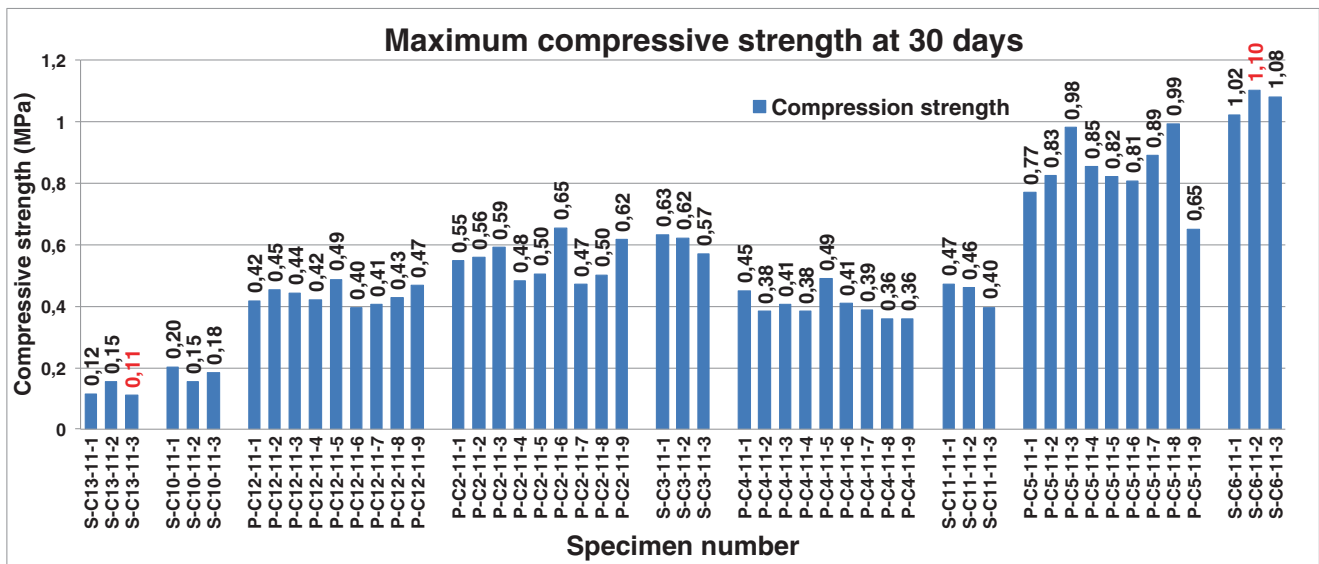


Fig. 2.6 Compressive strength results for different hemp concrete

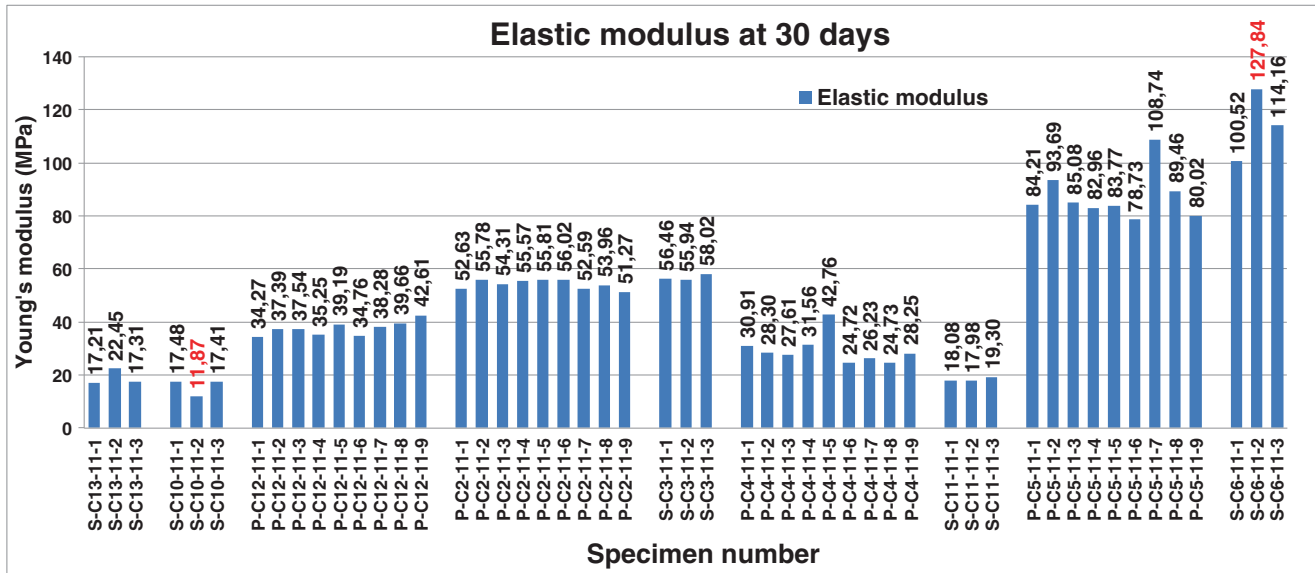


Fig. 2.7 Elastic modulus results for different hemp particles

Table 2.3 Summary of results at 30 days

	Specimen number	Maximum strength	Strength at 5 % of strain	Apparent modulus	Elastic modulus
Mean value	P-C2-11	0.55	0.51	29.49	54.22
	P-C4-11	0.40	0.34	15.00	29.45
	P-C5-11	0.84	0.79	46.77	87.41
	P-C12-11	0.44	0.40	16.39	37.66
	S-C3-11	0.61	0.60	33.49	56.81
	S-C6-11	1.07	1.05	61.00	114.17
	S-C10-11	0.18	0.16	4.89	15.59
	S-C11-11	0.44	0.22	6.17	18.45
	S-C13-11	0.13	0.05	5.68	18.99
Standard deviation	P-C2-11	0.06	0.03	6.06	1.73
	P-C4-11	0.04	0.04	4.74	5.53
	P-C5-11	0.11	0.08	13.17	9.20
	P-C12-11	0.03	0.02	1.43	2.67
	S-C3-11	0.03	0.03	3.38	1.08
	S-C6-11	0.04	0.03	15.53	13.66
	S-C10-11	0.03	0.02	1.72	3.22
	S-C11-11	0.04	0.01	0.15	0.74
	S-C13-11	0.02	0.04	1.42	3.00
Coefficient of variation	P-C2-11	11.59	6.15	20.56	3.19
	P-C4-11	10.53	12.19	31.63	18.78
	P-C5-11	12.48	10.47	28.17	10.53
	P-C12-11	6.90	4.92	8.75	7.09
	S-C3-11	5.62	4.66	10.10	1.91
	S-C6-11	3.82	2.59	25.46	11.96
	S-C10-11	14.18	11.77	35.26	20.64
	S-C11-11	9.21	2.80	2.42	3.99
	S-C13-11	19.05	86.62	24.92	15.79

The detailed results for all samples (3 for secondary test and 9 for primary test) allowed us to show the variability within a given hemp particles type as illustrated in Figs. 2.6 and 2.7 for both compressive strength and moduli, respectively. For a detailed analysis, the Tables 2.3 and 2.4 give the mean values of all specimens for each hemp particles, the standard deviation and the coefficient of variation. These results are given at 30 days and 180 days, respectively.

Table 2.4 Summary of results at 180 days

	Specimen number	Maximum strength	Strength at 5 % of strain	Apparent modulus	Elastic modulus
Mean value	P-C2-11	0.57	0.55	29.09	58.84
	P-C4-11	0.42	0.31	15.09	33.12
	P-C5-11	0.87	0.82	40.42	88.97
	P-C12-11	0.42	0.36	14.12	35.22
	S-C3-11	0.66	0.61	30.99	55.98
	S-C6-11	1.07	1.02	42.79	103.44
	S-C10-11	0.25	0.18	7.68	20.94
	S-C11-11	0.40	0.21	10.91	20.08
	S-C13-11	0.13	0.10	12.27	20.72
Standard deviation	P-C2-11	0.04	0.03	4.36	6.72
	P-C4-11	0.07	0.08	2.95	5.95
	P-C5-11	0.06	0.06	12.09	11.90
	P-C12-11	0.07	0.05	1.21	4.84
	S-C3-11	0.05	0.04	3.42	4.54
	S-C6-11	0.14	0.15	14.94	22.93
	S-C10-11	0.00	0.00	1.15	0.78
	S-C11-11	0.05	0.01	2.15	1.78
	S-C13-11	0.02	0.05	4.76	4.70
Coefficient of variation	P-C2-11	7.68	5.08	14.99	11.42
	P-C4-11	17.16	24.32	19.52	17.97
	P-C5-11	6.72	7.90	29.90	13.38
	P-C12-11	15.68	13.82	8.58	13.75
	S-C3-11	7.15	6.69	11.05	8.11
	S-C6-11	13.45	14.18	34.92	22.17
	S-C10-11	1.96	0.91	15.00	3.72
	S-C11-11	13.40	3.92	19.67	8.85
	S-C13-11	15.41	50.71	38.77	22.67

2.3.3 Variability of Result with Respect to Used Hemp Particles

2.3.3.1 Compression Strength

Due to the different levels of deformability, especially in the case of high deformation, it is not relevant to assess the compression strength by considering only its maximum value. Because, as discussed early, some types of hemp may be compressed up to high level of deformation, almost infinitely, without breaking (Fig. 2.5c). Therefore, the deformation level reached does not necessarily correspond to the allowable deformation in practice. For this matter, it is important to analyse the compressive strength by considering the associated strain. As result, in the herein study we discuss not only the maximum compressive strength but also the compressive strength at 5 % of strain.

According to the obtained results, significant differences are observed with respect to hemp particles type used with a factor equal to 8.2 between the lowest mean value of maximum strength and the highest one, this is the case for hemp C13 and C6, respectively. The obtained coefficient of variation in the case of maximum compressive strength and at 5 % of deformation varies from 1 to 25 % for all criteria (type of hemp, date of test, etc.). This shows to what extend hemp particles induce variability in results.

However, in some cases, we observe a relatively high coefficient of variation as for C13 with 86.62 % at 30 days, or 50.71 % at 180 days for the same hemp particles. Note that these dispersions are observed for the compressive strength at 5 % of strain. Indeed, since C13 has low levels of deformation as shown in Fig. 2.2, it follows that the compressive strength values obtained at 5 % are too dispersed.

2.3.3.2 Modulus

Since it is known that there is a relationship between compressive strength and modulus, one can expect to have the same variability for modulus results as for compressive strength ones. However, the analysis in the case of modulus indicates that these dispersions are not necessarily the same.

The mean values obtained vary from 4.89 MPa to 61.00 MPa and 15.59 MPa to 114.17 MPa for the apparent and elastic modulus, respectively. Such dispersions are obtained by considering different types of hemp particles and both testing dates. Furthermore, in the same configurations, the observed coefficient of variation varies from 2.4 % to 38.8 % and 1.9 % to 22.7 % for the apparent and elastic modulus, respectively.

2.4 Conclusion

In this study, the problem for suitable hemp concrete mixer has been discussed and it has been highlighted that the use of classic mixer result in non-homogeneous mixture. The results of the study show that hemp particles may impact considerably the hemp concrete mechanical properties. By changing only hemp particles, a factor of 10 has been observed between minimum and maximum values for compressive strength. It has also been highlighted the three main mechanical response behaviors for hemp concrete material characterized by the low, medium and high level of strain. These observed behaviors are related to hemp particles shape and their water absorption capacity. It has also been highlighted that probably the hemp particles/binder chemical interaction may also impact the observed behavior, thus, it is necessary to undertake more investigations, which may focus on the chemical composition and molecules in plant cell surface as they may affect significantly the setting and hardening process for the binder.

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