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RRT3: STATISTICAL ANALYSIS OF HEMP CONCRETE MECHANICAL PROPERTIES VARIABILITY

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Abstract

The study has been carried out in the context of a working group within the RILEM Technical Commitee 236-BBM 'Bio-aggregate-based building Materials'. It focusses on statistical analysis of hemp concrete properties. The objective is to determine statistically the variability for material density, compressive strength and Young's modulus. The considered parameters are: the testing laboratory equipment, the hemp shiv type, the batch and the specimen size. Two types of hemp shiv have been used with two batches for each one. Two specimen sizes were used: 11x22 cm and 16x32 cm. Specimens were manufactured in one laboratory in order to ensure the homogeneity of studied material. After 90 days of drying under the same conditions, they were transported to ten different laboratories for compressive testing. A drying protocol during 48 hours was applied by all laboratories. Then, a unique protocol for compressive testing has been applied by each laboratory. Finally, data have been collected together for statistical analysis. The obtained results show an accurate repeatability for the compressive strength and the dry density; however, the Young's modulus results show a large variability.

Keywords:

Hemp concrete; mechanical properties; hemp concrete scatter

1 INTRODUCTION

The use of plant origin aggregates is nowadays considered as an essential way in manufacturing environmentally friendly building materials. Many aggregates of this kind exist and are used in the construction industry, either in new structures or for renovation of existing buildings, such as, aggregates of sunflower and hemp shiv [1–3].

In contrast to aggregates of mineral origin, plant origin aggregates are renewable and carbon neutral materials. They also have other advantages such as good thermal and acoustic insulation properties. However, the major drawback is related to their low mechanical performance [4–6]. Therefore, in the framework of the present study, the herein literature review focuses on concrete made from hemp shiv, and particularly on its mechanical behavior and density.

Parameters influencing the properties of hemp concrete include among others: the aggregate nature and size, the type of binder and manufacturing method (compaction energy, molding method, etc.) [7, 8].

For ten different formulations, Cerezo [7] obtained the final average density values ranging from 256 kg/m^3 to 782 kg/m^3. Although she consided in analysis that the series have a low dispersion, this is not true at all levels. This is only valid at the intra-formula level, but not for at the inter-formula level, because in this latter case, considerable dispersion is observed for both final and initial mean values; which vary in the range of 455 kg/m^3 to 1140 kg/m^3. Another study has been conducted by Nguyen [8] on two types of hemp shives: the first with pure shiv particles (CP), while the other one contains fibers (CF). It has shown that there is no difference between the two shives in terms of density. For specimens tested under the same conditions, the observed difference was less than 2%. The obtained results were in the range of 450 kg/m^3 to 800 kg/m^3 at 90 days. This dispersion is mainly based on three main parameters of formulation and manufacturing process, namely the binder/aggregate ratio; the water/binder ratio and the compaction strength.

Nguyen [8] also highlighted the parameters influencing the compressive strength. Because of the low rigidity of particles, hemp concrete has a very ductile behavior in both compression and tension. Based on test results, he obtained a compressive strength, for a strain equal to 7.5% after 28 days, which varies between 0.2 MPa and 3.6 MPa. On her side, Cerezo [7] obtained the compressive strength ranging between 0.25 and 1.15 MPa. For low binder content, the compressive strength is around 0.25 MPa. For intermediate dosage, it varies between 0.4 and 0.8 MPa and for high binder content, it is 1.15 MPa. She concluded that mechanically, hemp concrete is characterized by an elastic-plastic behavior, and that this material must be used with a support structure to meet structural requirements.

Other parameters may also influence the mechanical behavior of hemp concrete such as drying conditions, the age of hemp concrete and the size of hemp particles [9]. Taking into account these parameters, Arnaud and Gourlay [9] obtained compressive strength, which varies between 0.35 MPa and 0.85 MPa for the age of 21 days to 24 months.

Young's modulus values found in the literature have also high variability and the methods used for its calculation are also different. According to Cerezo [7], the Young's modulus is defined as the slope at the origin of the strength-strain curve by considering the validity of the small strain assumption. Young's modulus varies from 1 to 3 MPa for low binder content; 32 to 95 MPa for intermediate dosages and 100 to 160 MPa for high dosage. For various formulations, Nguyen [8] obtained, at 90 days, the Young's modulus between 25 MPa and 176 MPa, using pure hemp particles. According to his study, the Young's modulus of a given specimen is calculated based on the strongest increase in the ratio strength/strain recorded at the beginning of the loading stage.

The results in the literature show that the values for properties of hemp concrete have a great variability and are sensitive to many factors. The literature shows also that there is a lack on the consideration of the accuracy of testing instruments used and the variability of results due to experimentations. For this reason, other statistical studies are required to assess the certainty and variability of the results for the properties of hemp concrete.

In the present study, a statistical analysis of the results taking into account two types of hemp shives, four types of batches, and two specimen sizes, is carried out in order to analyze the variability on experimental results. The considered properties are: density, compressive strength and Young's modulus.

2 MATERIAL AND METHODS

The specimens in this study, were manufactured using two hemp shives with the same binder, prompt natural cement (PNC) and citric acid. The characterization results for bulk density, water absorption and particle size distribution, are given for both shives in *Table 5*.The protocols and methods related to manufacturing, mixing process and compressive testing are given in sections 2.2 and 2.3. The compressive tests have been made using different machines under the same protocol, and the experimental results were collected for statistical analysis. The considered parameters during the mixing and manufacturing process are provided in Table 1.

Table 4: Summary datas for specimens of the study

Specimen sizes		**Specimen 11cmX22cm**				**Specimen 16cmX32cm**				**Total per laboratoire**
Type of batch		**I**	**II**	**III**	**IV**	**I**	**II**	**III**	**IV**	
Laboratory name	**Institut Pascal (A)**		3		3		3			9
	Belfast (B)		2	2						4
	Trinity (C)	2			2					4
	LMDC Toulouse (D)	2		2						4
	Bath univ (E)		3		3					6
	LGCGM Rennes (F)		3		3				3	9
	Vicat (G)	3	1	6				3		13
	IFSSTAR (H)		3		4					7
	LiMATB Lorient (I)	3		3		3				9
	Lhoist (J)	2		2						4
Total per batch		**12**	**15**	**15**	**15**	**3**	**3**	**3**	**3**	**69**
Total per specimen size		**57**				**12**				

2.1 Shiv

The shives used in this study come from the same producer, but they were produced in two different series and stored in two separate places before use. One bag with the reference 13 0173 KANABAT at the ENTPE laboratory, noted S1 shiv, and the other one at Vicat laboratory with the reference 13 0174 KANABAT, noted S2 shiv. Samples, of about 1 kg each, have been taken and characterization tests were conducted according to the protocol in [10,11]; results are given in Table 5.

Table 5 : Characteristics of used shives

		S1	S2
Water absorption (%)	Initial mass	212	153
	Final mass	390	334
Bulk density (kg/m^3)		143.6	147.5
Particle size distribution	Specific area (mm^2/3g)	13913	13187
	Minor axis (mm)	1.38	1.22
	Major axis (mm)	5.10	5.58
	Feret diameter (mm)	2.57	2.53

2.2 Mixing of hemp concrete and casting method

For a batch of 80 liters, each constituent is weighed in buckets. The shiv (8kg) is put in the mixer, then the PNC (20kg) with Citric Acid (0.06kg) is introduced; they are then mixed with 40% of the mixing speed for few minutes. Water (19.2 kg) is added and the mixing is retained. The mixing speed is increased to 50% then kept until homogeneous mixture is obtained. Finally, the mixer is emptied into a wheelbarrow.

Then, the mold is filled with 5 to 6 layers; two consecutive layers must be compacted using a suitable tool. For the last layer, the upper surface is kept smooth and the specimen is weighed. A cover is put and the specimen is kept returned for a period of at least 72 hours after which the cover and the bottom are removed. The specimen is then kept at 20°C and 55% of relative humidity for 90 days.

To ensure that the tested specimens are identical, they were manufactured at the same day and were dried for 90 days under the same conditions at the laboratory G. After this drying period, samples were transported to ten different laboratories for compression testing.

2.3 Protocol of compressive test

Tests were done under the same conditions, the detailed below protocol, was carefully followed by all laboratories. Specimens were dried in an oven at 50°C for 48 hours before the compressive test.

1. Weighing the specimen with the mold; then remove the mold using a cutter: remove the sample ends then cut just the surface of the mold; and mark it with the same reference on the mold;
2. weighing the specimen without the mold; then put it in an oven at 50°C until a stabilization of weight equal to +/-2%; and leave it in a sealed plastic bag until the test day;
3. before the test, measure three diameters (at top, bottom and middle) and the height every 120°;
4. no surfacing of the sample and a perfect parallel plates is made before the starting the test;
5. the test must be displacement controlled at the rate of 3mm/min for loading stage. The unloading stage should be 6mm/min or free if it is not possible to control it;
6. applying three load cycles depending on the specimen size: 1st cycle: loading is done from 0 to 1% of relative deformation and unloading until zero load or zero displacement; 2nd and 3rd cycles are the same as the 1st, the strain is always increased by 1% for each cycle. The final loading is: from 0 until the total failure load of the specimen (maximum of 20% of strain) and unloading until zero load (when possible) or zero displacement.

Voluntarily for some specimens, in the case of lab C, the compressive tests were done with a monotonic loading.

2.4 Young's modulus calculation method

According to the frequency of data acquisition (nearly 10Hz or 10 values per second, Figure): the loading steps are identified then the floating modulus is calculated in each step using: $E=\frac{\Delta\sigma}{\Delta\varepsilon}$; where E is the modulus around a given point, $\Delta\sigma$ and Δε are strength and strain respectively considered between -5 and +5 seconds around the considered point. The maximum modulus is then identified for each step. The floating Young's modulus value is therefore, the mean value of the maximum values obtained at the 2nd, 3r^{d} and 4th loading steps.

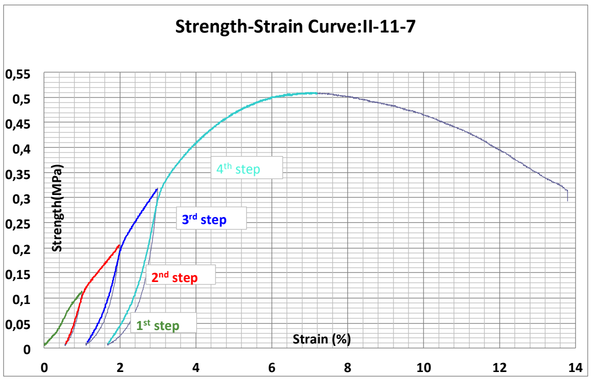

Figure 1: Identification of the loading steps to calculate the floating Young's modulus

2.5 Characteristic values and Coefficient of variation (COV)

The characteristic value of a design parameter corresponds to the representative value to be included in the computation procedure for a purpose of design, maintenance or rehabilitation or any other decision process. For example, the compressive strength of concrete is defined as the resistance below which there are only 5% of test results [12]. Under the assumption of normality, it is proposed to calculate the characteristic value of concrete compressive strength as follows:

$$f_{ck} = f_{cm} - 1.645\sigma_{fc} \quad (1)$$

where f_{ck} is the characteristic value, f_{cm} is the average value of all the test results and σ_{fc} is the standard deviation of test results; the coefficient 1.645 corresponds to a 5% quantile of the normal Gaussian distribution. It is to note that all experimental results were subjected to the test of normality and the test was not rejected. Then formula in (1) is used in our study with the probability level of 5%.

The coefficient of variation (COV) indicates the dispersion of the experimental results; it is calculated by the ratio between the standard deviation (SD) and the mean value (MV), in (%). Table 6 gives accepted limits of coefficient of variation for concrete [13].

3 RESULTS AND DISCUSSIONS

In order to simplify the notations, the following abbreviations are used: MV for the Mean Value, SD for the Standard Deviation, COV for the Coefficient Of Variation and CV for the Characteristic Value.

Table 6: Accepted limits of variability of concrete compressive strength as a function of the quality control [13]

Quality control	Accepted limits for the COV
A (excellent)	10
B (average)	15
C (poor)	20

3.1 Repeatability of the results between testing laboratory

As seen, the density, the compressive strength and the Young's modulus may vary according to many parameters such as: compaction energy [7,8], measuring method [14] and hemp shiv type [9]. In this section, analyses for results in tables 5 and 6 focus on the impact of testing laboratories.

Table 7 : Density, maximum compressive strength and Young's modulus values per laboratory, specimens 11x22cm

	Density (kg/m^3)				Compressive strength (MPa)				Young's modulus (MPa)			
Lab name	**MV**	**SD**	**COV**	**CV**	**MV**	**SD**	**COV**	**CV**	**MV**	**SD**	**COV**	**CV**
All lab	471.22	28.28	6.00	424.84	0.45	0.05	10.69	0.37	36.86	7.08	19.22	25.24
A	496.88	31.25	6.29	445.63	0.49	0.03	5.46	0.45	33.82	4.58	13.55	26.31
B	476.93	17.64	3.70	448.00	0.48	0.04	8.45	0.41	40.72	5.01	12.29	32.51
C	471.44	29.14	6.18	423.65	0.44	0.03	6.73	0.39		Not available[1]		
D	465.95	18.47	3.96	435.65	0.42	0.06	13.87	0.32	34.16	3.43	10.05	28.53
E	468.44	29.35	6.27	420.31	0.49	0.02	4.47	0.45	40.87	8.63	21.13	26.71
F	465.20	26.58	5.71	421.61	0.49	0.04	8.36	0.42	35.27	3.18	9.02	30.05
G	453.72	12.96	2.86	432.47	0.41	0.04	9.42	0.34	35.33	5.11	14.45	26.96
H	472.48	35.16	7.44	414.82	0.46	0.05	10.56	0.38	44.01	9.89	22.47	27.79
I	452.71	12.64	2.79	431.99	0.45	0.05	10.78	0.37	36.01	5.23	14.53	27.43
J	514.62	15.53	3.02	489.16	0.43	0.04	8.30	0.37	28.81	4.75	16.49	21.02

[1] Results are not available as the compressive test is monotonic loading which is not compatible with calculation Young's modulus method used

Table 8 : Density, maximum compressive strength and Young's modulus values per laboratory, specimens 16x32cm

	Density (kg/m^3)				Compressive strength (MPa)				Young's modulus (MPa)			
Lab name	**MV**	**SD**	**COV**	**CV**	**MV**	**SD**	**COV**	**CV**	**MV**	**SD**	**COV**	**CV**
All lab	443.53	29.70	6.70	394.81	0.38	0.06	16.77	0.28	35.58	4.46	12.54	28.26
A	423.41	1.96	0.46	420.20	0.32	0.02	5.07	0.29	30.97	2.28	7.35	27.24
F	495.45	8.56	1.73	481.42	0.48	0.02	4.47	0.44	39.13	3.04	7.77	34.14
G	445.47	4.10	0.92	438.74	0.39	0.00	1.17	0.39	32.77	2.95	9.02	27.93
I	420.38	2.10	0.50	416.93	0.32	0.01	4.15	0.29	39.06	3.42	8.76	33.45

Density

The analysis of the results obtained by different labs shows small variability for a given specimen size; with a COV of 6.0% and 6.7% for all labs in both cases small and large specimens respectively, as shown in tables 5 and 6. The observed difference in the characteristic values of the density, when comparing both specimen sizes will be discussed in section 0.0. Within each category of a specimen size, the observed results have excellent quality with reference to the accepted limits in Table 6.

Maximum compressive strength

For small specimens 11x22cm, the compressive strength results show values ranging from 0.32 MPa for lab D to 0.45 MPa for labs A and E, as shown in Table 7. In general, there is no considerable variability in the obtained results. The method and used machines give similar results for the characteristic strength with 10.69% of COV for all labs. In case of large specimen size, the COV is 16.77% for all labs, as shown in Table 8, this high variability leads to poor quality of the strength. For small specimen size, the quality is excellent with average COV close to the accepted limits as given in Table 6.

Young's modulus

The results taking into account the impact of testing laboratory on the evaluation of Young's modulus show mean values ranging from 28.81 MPa to 44.01 MPa. In fact, we have two classes of values, one in the interval from 33 MPa to 38 MPa, and the other in the interval from 40 MPa to 45 MPa, the value of lab J looks like an isolated case. For larger specimen size, the results seem to be homogeneous with a maximum COV equal to 9.02%. These results must be analyzed carefully as the number of specimens is not statistically large. Two laboratories have high COV values of 22.47% and 21.13%, leading to a COV for all laboratories equal to 19.22 % (Table 7). With such COV, the results are of poor quality compared to the limits in Table 6. There is a significant impact of the testing laboratory on the Young's modulus where the obtained results have poor quality, although the obtained results have excellent quality for the compressive strength. This has to be considered carefully, since it is known that there is a strong correlation between the Young's modulus and the compressive strength. The main explanation to this observation is the nonlinear behavior of strength-strain curve, because the maximum strength is located beyond the linear part of the curve, Figure .

3.2 Repeatability of the results between batches

Although the batch type is not yet studied in the literature, to our knowledge, this parameter may influence the results as shown in Table 9.

Table 9 : Maximum compressive strength and Young's modulus values per batch, specimens 11x22cm and 16x32cm

	Compressive strength (MPa)				Young's modulus (MPa)			
Batch type	MV	**SD**	**COV**	**CV**	**MV**	**SD**	**COV**	**CV**
I. (11x22cm)	0.41	0.04	9.78	0.35	30.46	3.81	12.52	24.21
II. (11x22cm)	0.47	0.04	8.18	0.41	33.35	3.85	11.53	27.04
III. (11x22cm)	0.44	0.05	10.93	0.36	38.04	4.54	11.94	30.59
IV. (11x22cm)	0.48	0.04	8.16	0.42	44.07	7.46	16.93	31.84
I. (16x32cm)	0.32	0.01	4.15	0.29	39.06	3.42	8.76	33.45
II. (16x32cm)	0.32	0.02	5.07	0.29	30.97	2.28	7.35	27.24
III. (16x32cm)	0.39	0.00	1.17	0.39	32.77	2.95	9.02	27.93
IV. (16x32cm)	0.47	0.02	4.51	0.44	39.13	3.04	7.77	34.14

Maximum compressive strength

The results for compressive strength show that the values for batch IV are higher for both specimen sizes than in the case of Young's modulus. Batches from S2 seem to have high values as shown in Table 9. This trend is analyzed in section 3.3 where the impact of both shives is studied. As it will be discussed in the next section for the Young's modulus, the compressive strength shows some variability for different batches, therefore the mixture in different batches must be carefully performed.

Young's modulus

The mean values of Young's modulus increase form Batch I with 30.46 MPa to Batch IV with 44.07 MPa as given in Table 9. There is no explanation for this observed trend. However, even with this trend, it is clear that batches from the same shiv have comparable results. In batch IV, the COV equal to 16.93% is greater than for other batches, as this one has been manufactured at last, maybe the operators did not maintain the same conditions (e.g. compaction energy…) from the beginning up to the end. As this trend is not the same as for large specimens, the justification given above is not necessarily true. For both cases (small and large size specimens), an average quality is observed, with respect to the limits in Table 6. This means that the batch does not have a great impact on the results, but sometime it may cause variability, as it is the case for batch IV. Therefore, it is necessary to be careful when mixture is done using different batches.

3.3 Repeatability of the results for different hemp shiv types

Arnaud and Gourlay [9] studied the impact of hemp shiv; they concluded that the use of smaller shiv results in hemp concretes with higher mechanical properties at long term. Nguyen [8] compared two shives; one pure and the other contains fibers; as conclusion to its study there was no big difference on their mechanical properties. In our study, some differences have been observed, according to the results given in Table 7.

Table 10 : Density, maximum compressive strength and Young modulus values per hemp shiv

	Density (kg/m^3)				Compressive strength (MPa)				Young's modulus (MPa)			
Hemp shiv	**MV**	**SD**	**COV**	**CV**	**MV**	**SD**	**COV**	**CV**	**MV**	**SD**	**COV**	**CV**
S2 (11x22cm)	488.88	23.11	4.73	450.97	0.46	0.05	10.38	0.38	43.45	6.72	15.47	32.43
S1 (11x22cm)	451.61	19.17	4.25	420.16	0.44	0.05	10.79	0.37	31.86	3.14	9.87	26.71
S2 (16x32cm)	469.78	27.08	5.76	425.38	0.43	0.05	10.58	0.36	32.77	2.95	9.02	27.93
S1 (16x32cm)	422.10	2.51	0.60	417.98	0.32	0.01	4.00	0.30	30.97	2.28	7.35	27.24

Density

If we compare both hemp shives in terms of density, we observe slight difference between the obtained densities, even with different specimen sizes. We obtain 420.16kg/m^3 and 450.97kg/m^3 with 417.98 kg/m^3 and 425.38 kg/m^3 characteristic values for S1 and S2 for both small and large specimen sizes respectively as shown in Table 7. Large values have been observed for S2, which is consistent with the drying kinetics.

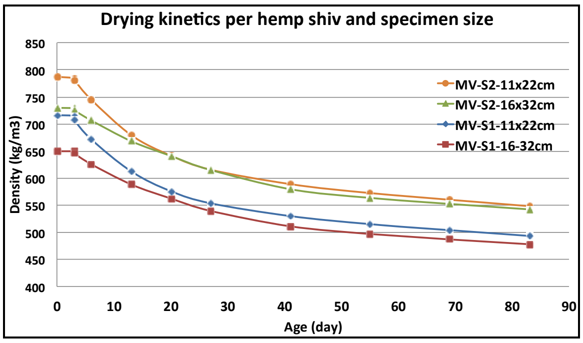

Figure 2: Drying kinetics per hemp shiv and specimen size

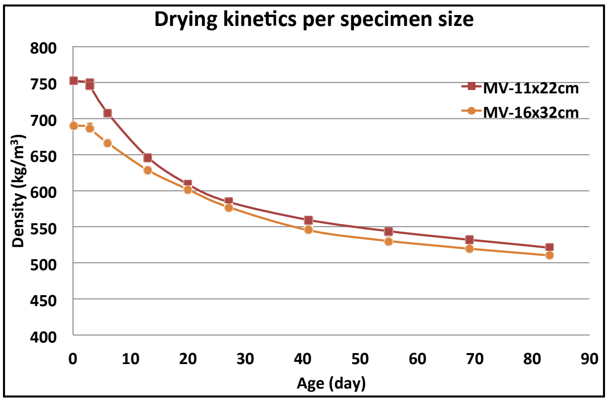

Figure 3: Drying kinetics per specimen size

According to the drying kinetics in **Erreur ! Source du renvoi introuvable.**, it appears that the drying is only affected by the specimen size, which seems normal, because they dry faster since they have a greater specific area than larger specimens. On the other hand, a difference in fresh density is also observed depending on both specimen sizes and hemp shiv types. Small specimens have a higher fresh density than the large specimen which could be explained by a greater compaction (same "compaction energy" applied by the operator on a smaller area). The specimens made from S2 have a higher fresh density than those from S1, which means that, they were more compacted. The initial water content measured are 10,18% and 11,12% for S1 and S2 respectively. This difference in initial water content between S1 and S2 confirms our results. As the water content of the S2 was higher than in S1, the initial absorption of water were reduced (which is the case according to results in Table 5) and S2 was more easily compacted which explain the high value of fresh density.

Maximum compressive strength

The observed compressive strength results are 0.38 MPa and 0.37 MPa for small specimen size; with 0.36 MPa and 0.30 MPa for large specimen size both for S2 and S1, respectively. The maximum strength values for S2 are greater than for S1; this trend is the same for Young's modulus.

Young's modulus

For both specimen sizes, results show that Young's modulus values for S2 are greater than for S1. We also have a high variability for S2 with a COV equal to 15.47%. This is probably due to the fact that batch IV is for S2 and as shown in the previous section, there is a high variability within this batch.

With respect to the type of shiv, in both cases of Young's modulus and compressive strength: these differences can be explained by the fact that, since S2 has a small specific area 13187mm2, versus 13913mm2 for S1, the hemp particles are better coated by the binder during the mixing process of the concrete, which may explain this better mechanical properties of the hemp concretes made from S2. This remark is similar to the results obtained by Arnaud [9] where he remarked that after 4 months, the finer hemp particles gave better mechanical properties than longer hemp particles. This difference may be also justified by the fact that the initial water absorption of S2 is 146% and for S1 is 212%. This means that S1 absorbs a lot of mixing water and this results in a dry mixture, leading to poor mechanical properties. To avoid this problem, shiv particles may be wetted before the mixing process.

3.4 Repeatability of the results with respect to specimen sizes

Density

Although the results for each specimen size are not varying too much, density characteristic values obtained for both sizes are 424.84 kg/m3 and 394.81 kg/m3 for small and big size respectively, (tables 5 and 6). Unlike to what is observed in the case of the maximum compressive strength, there is no difference for the COV values, as discussed in 0.0, there are always great values for small specimen size.

Maximum compressive strength

Considering the results obtained for the characteristic values 0.37 MPa and 0.28 MPa for small and big specimens, respectively (tables 5 and 6), the specimen size does not have exactly the same trend for the compressive strength as for Young's modulus. Since there is no big difference for minimum, maximum and mean compressive strength values, then the observed difference for characteristic values is related to the COV values.

Young's modulus

Results on the impact of specimen size in the case of Young's modulus show comparable values for the mean and characteristic values, (tables 5 and 6). A significant difference is observed for the maximum values with a factor equal to 1.32.

4 CONCLUSION

The statistical analysis has been performed for the considered properties, namely the density, the compressive strength and the Young's modulus by taking into account four parameters: testing laboratory, batch type, hemp shiv type and specimen size. The results obtained by different laboratories show that there is an accurate repeatability for the compressive strength and the dry density. However, the results for the Young's modulus are of a large variability, with results varying from excellent to poor quality. The results also showed that there is some variability between different batches, and therefore the mixing procedure must be done with an utmost care. The impact of initial water content on the density has been also highlighted. More initial water content is, less will be the density of hemp concrete made from it. We have also noticed that the hemp with small particle sizes results in better mechanical properties.

According to the obtained results, plausible evidence for specimen size effect was observed. However, in our study we could not have enough data (limited number of specimens 16x32cm), to highlight the effect of specimen sizes. Further investigation on a statistically significant number on specimens of different sizes, would better allow us to understand the effect of specimen size.

This study will be enhanced by works in hand on statistical analysis, in which the shifting of mean values of batches to a mean of reference allowed us to group the results into one population, with the aim of characterizing the scatter and the distribution type. Therefore it will be possible to computer characteristic value taking into account all parameters for each property.

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