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Fuzzy logic response to Young's modulus characterization of a flax–epoxy natural fiber composite

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ABSTRACT

Most design approaches use the experimental elastic modulus as input variable to describe the material properties. In most cases the uncertainty and the variability of the modulus are neglected. In the worst case this can lead to bad estimations of the material performance and more iterations to the final solution. The purpose of this work is to reconcile the Young's modulus of three configurations ($[0]_{10}$, $[0]_{20}$ and $[\pm 45]_{10}$) of flax–epoxy composites obtained by different techniques including acoustic impulse, tensile and bending tests, according to ISO and ASTM standards. Results obtained with these techniques all show different levels of variability in Young's modulus values. A fuzzy logic model is used to obtain a simplified view of linguistic variables representing the modulus of elasticity and to reconcile different modules by including the uncertainty inherent to the different measuring techniques. Results have shown a strong potential for fuzzy logic to reconcile the disparity of Young modulus of natural fiber composites.

1. Introduction

In addition to be considered eco-friendly materials, natural fiber composites (NFCs) have interesting mechanical properties and compete with non-degradable materials in several fields of application [1,2]. Indeed they present low density, good mechanical properties, low cost, and ease of machining [3]. However the disparity of their properties, which results in variability of their behavior, prevents the growth of their use, unlike synthetic fiber composites. Many authors [4–7] have demonstrated that the NFC, specifically the flax–epoxy composite has a large dispersion in its mechanical properties. Therefore, repeated measurements in equal conditions using different samples will give a variation in measurement results. For the same flax–epoxy material, there is also a noticeable difference between tensile and flexural modulus. Table 1 shows the compiled results of tensile modulus for unidirectional (UD) and weave varieties of flax–epoxy composites. Though this list is not exhaustive, it provides a snapshot of the variability of estimated values of tensile modulus. It can be observed that the tensile modulus depends on fiber volume fraction and the nature of epoxy used in the matrix, the process used and the fabric type of fibers. For woven fabrics the amount of waviness in the yarns may also affects tensile modulus [8]. To assess their sustainability and promote the use of these materials in the industry, their mechanical behavior must be carefully studied [9].

Lord and Morrell [10] conducted a study to identify the sources of uncertainty in the calculation of the tensile modulus. They demonstrated that the accuracy in modulus determination is strongly affected by the quality of the data acquired, the test set-up and the material availability. From these three parameters alone it is reported that the uncertainly can vary from 1% to 6%. Baley [6] observed a large spread of Young modulus's of flax fiber. The uncertainly of Young's modulus of flax fiber can reach up to 28% [5] while the uncertainly of glass fiber is around to 3% [11]. This dispersion is explained by many different parameters that influence the quality of fibers, in particular the varying morphology of individual natural fibers. This heterogeneity depends of the climate [12], maturity at harvest time [13], surface treatment [14,15], processing parameters, and the presence of variable proportions of porosity [16] in the material. In addition, variations in the amount of waviness in the yarns can affect the mechanical properties of woven fabric composites. On the other hand, the manufacturing method of flax–epoxy also has a great influence on the tensile properties of the composites. In particular the manufacturing process influences the flax fiber length and the length distribution [17].

The importance of elastic properties of materials for design and engineering applications is such that there are a large number of experimental techniques that have been developed to estimate them. These techniques can be classified into two groups: destructive and non-destructive methods. Destructive methods include tensile, compressive and flexural tests, etc. These methods measure directly the strain and the stress during the test. The elastic tensile modulus of fiber- reinforced plastic composite is typically measured in the strain range of 0.05 to 0.25% and 0.1 to 0.3% for ISO 527-4 and ASTM D3039 standard norms respectively. Shah et al. [18] have showed that although the apparent stiffness is fairly constant in this strain range (0.05 to 0.25%) for unidirectional E-glass–polyester composites, there is significant variation in the

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Table 1
Tensile modulus of different models of flax fibers from the literature.

Fabric type	Fiber fraction V_f (W_f)%	Epoxy type	Process	E_T (GPa)	E_F (GPa)	Reference
Weave Warp knit $[0/90]_2$	28	Araldite MY-750	Hand lay-up	14	15	[9]
UD	59 to 64	Epikote 828LVEL	Hand lay-up	32.1 ± 0.4	23	[10,11]
Weave Warp knit $[0/90]_2$	28	Araldite MY-750	RTM	14	17	[9]
Weave	54	Resin SP106	RTM	1.8	7	[12]
Weave Twill 2 × 2	31 to 36	Huntsman LY5150	Autoclave	9.1 ± 0.3 to 10 ± 0.2	5.2 to 9.2	[13–16]
UD $[0]_7$	40	HM 533	Autoclave	26 ± 1	18 ± 3	[17]
Weave $[0]_3$	(35.5)	Ampreg20	Resin infusion	6.86 ± 0.14–		[18]
Weave [0/90/0]	(35.1)	Ampreg20	Resin infusion	7.37 ± 0.15	–	[23]
UD	38	–	–	15.97 ± 1.37	–	[15]
UD	57	Epikote 828LVEL	Thermo-compress	26.3 ± 2.1	18	[10,11]

E_T = tensile Young modulus; E_F = flexural Young modulus; W_f = weight fraction V_f = volume fraction.

apparent stiffness for flax-polyester due to their nonlinear stress–strain curve. This nonlinearity has reduced the Young's modulus by 30% for this NFC. Beats et al. [19] have also observed major influence of the strain range on the variation of Young's modulus of flax–epoxy. Actually, there is not standard norms which define the exact strain range for the determination of tensile modulus value of NFCs. For ISO standard 527-4, several authors use two approaches (0.05 to 0.25% or 0.05 to 0.1% strain range) to measure the tensile modulus and obtain different values of tensile modulus.

Nondestructive methods include ultrasonic measurement (pulse-echo or through transmission) and impulse excitation technique (or resonance method) [20,21]. These techniques are based on knowing the dimensions and densities of the samples, and are therefore often called indirect methods. The resonance method measures the resonant frequencies of materials in vibrational modes. The elastic proprieties of the specimen are related to its mechanical resonance frequency. The pulse method measures the time for the ultrasonic pulse to travel through the specimen from the transducer. It is possible to calculate Young's and shear moduli of the material by the knowledge of the travel time for longitudinal and transversal ultrasonic waves. The advantage of nondestructive techniques compared to destructives ones is that they can measure a wide variety of specimen shapes and sizes. They are also characterized by a good measurement precision over a wide temperature range. The specimen is also easy to prepare. But this technique is very sensitive dimensional variations and the mass of the test specimen [20] and to the anisotropy of the material [22]. It is one of the major disadvantages for their application for determination of elastic constants of NFC.

Whether destructive or nondestructive, most techniques use several parameters that are often measured with uncertainty. Furthermore, these parameters differ depending on the various tools and/or standards used. It is agreed that the quality of assessment is limited due to sources of uncertainties arising at several levels and caused by the testing method, the influence of the environment, human factor, etc.

Current design approaches use determinist elastic proprieties variables as inputs to describe the mechanical properties of the material. In the worst cases, neglecting the uncertainly and variability can lead to a bad estimation of the performance or the damage of the material [23]. Despite this influence most of the reliability analyses techniques do not take into account the uncertainties and variability of these input variables. For NFC materials and flax–epoxy particularly, the inherently large dispersion of their mechanical proprieties (due to the variable quality of natural fibers and the variable experimental errors obtained from different characterization tools or techniques) can certainly lead to bad estimations of the performance and more iterations to the final solution. Most of the techniques cannot be compared or reconciled directly because they are measured in different units, but the precision and the repeatability of one method can be lead to have a confidence to one method that another. Therefore, using mean or median values to correlate or to reconcile the values obtained by different methods or standard norms can lead to bad estimations. For this, it will be important to develop new design approaches which consider the variability of the mechanical properties of NFCs and the uncertainly of the characterization process. Fuzzy logic (FL) stands among the new interesting approaches that incorporate all the variabilities and uncertainties in the analysis phase. This technique enables potential reconciliation of the tensile modulus values obtained by different techniques and standard norm.

The FL technique is a soft modeling tool which has been used for linear and nonlinear systems. Fuzzy logic theory was developed by

Table 2
Characteristics of «FlaxPreg BL 150».

Fiber fraction	By weight W_f	50%
Fiber fraction	By weight W_f By volume V_f	50% 45%
Weave pattern (warp to weft ratio)	1/1	
Fiber density ρ_f (g/cm^3)	1.45	
Weight of flax M_S (g/m^2)	150 g of weave/m^2	
Theoretical density of tissue ρ_c (g/cm^3)	1.31	

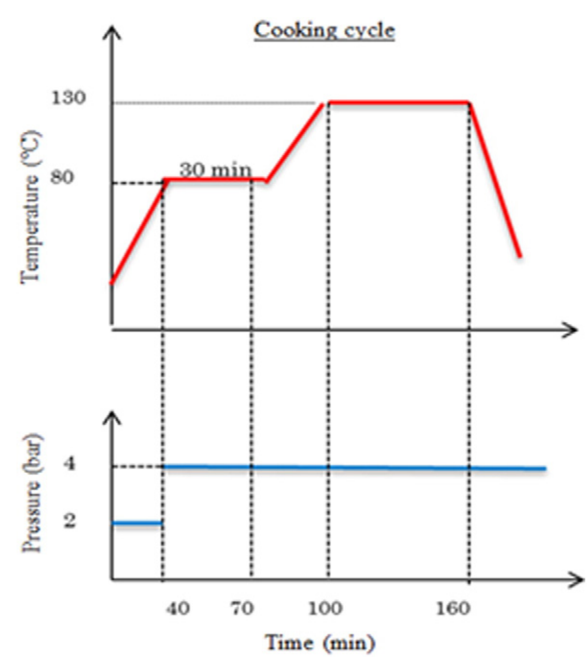

Fig. 1. Processing cycle applied during plate manufacturing.

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Table 3
Samples and measurement techniques performed in this research.

Sample	Acoustic impulse	Tensile		Flexural	
	ASTME 1876-09	ISO527-5	ASTM D3039	ISO 14125	ASTM D790
FE0	+ +	+ +	+ +	− −	− −
FE45	+ +	+ +	+ +	− −	− −
FEF	+ +	− −	− −	+ +	+ +

+ + = performed; − − = not performed.

Table 4
Characteristics of each specimen obtained by the acoustic impulse test: Mean value, standard deviation (±) and coefficient of variation (C_v) are given.

Specimens	ρ_c (g/cm^3)	Frequency (Hz) (C_v)	E-Impulse (GPa) (C_v)
FE0	1.12	563.04 ± 14.65 (0.026)	8.37 ± 0.18 (0.021)
FE45	1.11	83.47 ± 2,86 (0.031)	4.88 ± 0.10 (0.020)
FEF	1.12	2106.9 ± 8.49 (0.004)	9.65 ± 0.14 (0.014)

Zaded [24] in 1965 and was improved by Mandani [25] including inference rules (IF-THEN). Demir [26] used fuzzy logic to predict the modulus of elasticity of concrete with respect to the compressive strength. He found that the root mean square error (RMSE) obtained by this method was the lowest among various methods including regressions and different experimental codes. Ali and Neda [27] used fuzzy logic to predict the impact resistance for different thicknesses of aluminum–epoxy laminated composites obtained from experiments. Again here the RMSE obtained by the fuzzy logic model was the lowest. Many authors used generally FL to predict the mechanical properties of different material such as flakeboards [28], metal [29–32], and cement [33].

FL is actively used today in many different fields of engineering. For example Jaganathan et al. [34] recently used the range of input machining parameters, the "if then" rules and the triangular type membership functions of FL to predict the surface roughness and tool life of AISI M2 Steel.

The purpose of this paper is to use a fuzzy model to reconcile Young modulus obtained by different techniques (namely by tensile, three-point bending tests according to ISO and ASTM standards and impulse excitation technique). A novelty of the developed model is that the uncertainly of each testing method and the variability of mechanical proprieties of NFC are taken into account in the fuzzy model to see its influence on the final result.

2. Materials and methods

2.1. Prepreg characteristics

In order to evaluate the elastic properties of the material under study, plates of 30 cm × 25 cm were molded. Flax–epoxy prepregs plane weave from LINEO NV «FlaxPreg BL 150» were used for manufacturing the plates. The characteristics of this weave are summarized in Table 2. Lineo's FlaxPreg is usually used for the manufacture of a range of tennis racket and for the manufacture of a range of bicycles [35].

2.2. Composite fabrication

Manual cutting and stacking of uncured prepregs was done, yielding three types of samples in two orientations: ten successive stacks at 0° in the warp direction identified by FE0, twenty successive stacks at 0° in the warp direction identified by FEF, and ten stacks diagonally oriented at 45° identified by FE45. The laminates were manufactured in a compression molding machine (Carver Press, Wabash, IN, USA) at pressures of 2 and 4 bars. Fig. 1 shows the cure and pressure cycles applied during the plate manufacturing.

2.3. Specimen cutting

The cutting of the plates was done with a diamond blade cooled by water to avoid burning of the fibers. The geometric dimensions of the specimens meet the standards in ISO527-4 and ASTM D3039 for tensile tests, and ISO14125 and ASTM D790 for three-point bending tests. The dimensions of these rectangular specimens are 250 mm × 25 mm × 2.4 mm for tensile tests and 80 mm × 15 mm × 4 mm for flexural tests, respectively. After cutting, all the samples were placed in the oven at 70 °C for more than 24 h to remove the moisture. Table 3 presents different samples and the different measurement techniques used in this research.

2.4. Experimentation

2.4.1. Impulse excitation technique

Impulse excitation technique was carried out first in order to use the same samples in the tensile tests and three-point flexural tests. Five plates for each of FE0, FEF and FE45 were randomly selected. The samples were mechanically excited by automated tapping (Fig. 2). The vibration was recorded by a microphone and analyzed by the software "Resonant Frequency & Damping Analyzer (RFDA)" of the IMCE society. The resonant frequency f_f (in Hz) was found and the Young modulus

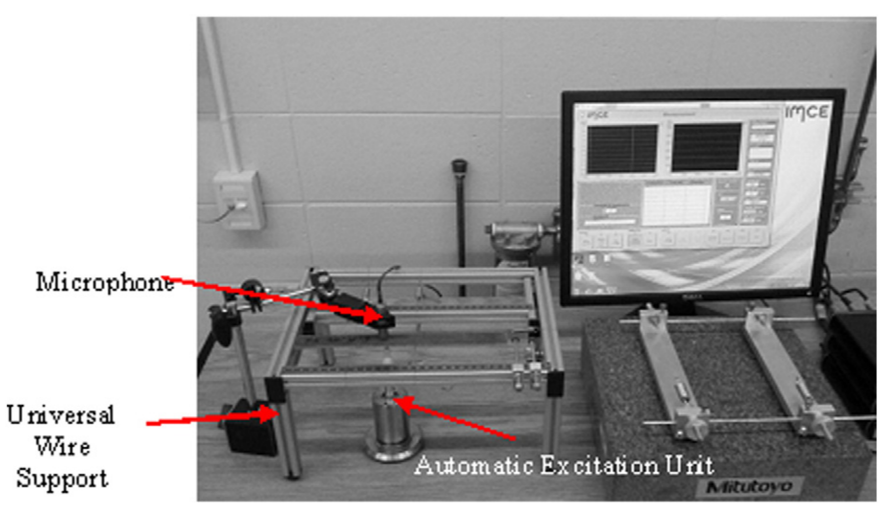

Fig. 2. Impulse excitation test measurement.

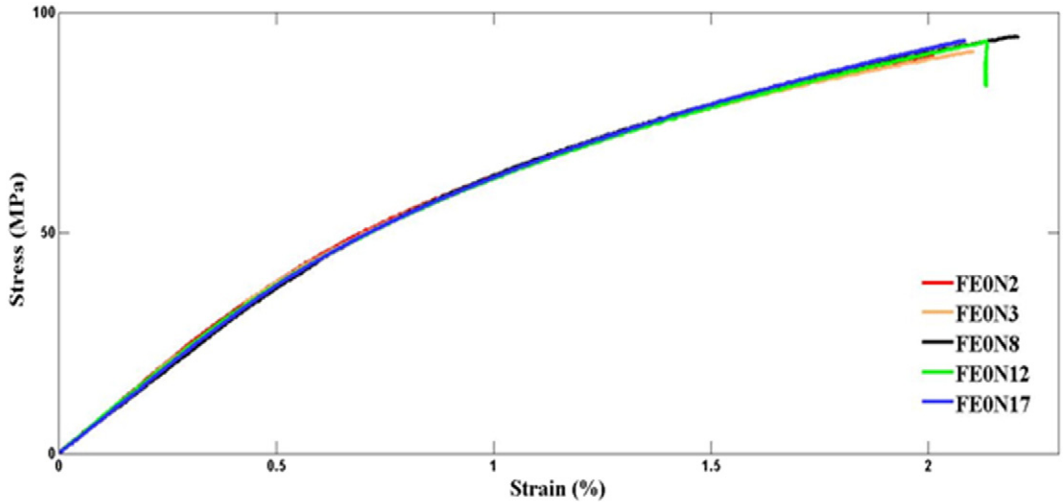

Fig. 3. Tensile stress–strain curves for FE0 sample.

Table 5
Tensile characteristics of each specimen.

Specimen	σ_R (MPa)	ε_R (%)	E-ISO (GPa) (C_v)	E-ASTM (GPa) (C_v)
FE0	92.61 ± 1.6	2.1 ± 0.06	7.97 ± 0.32 (0.040)	7.98 ± 0.28 (0.036)
FE45	76.8 ± 3,23	5.58 ± 0.20	4.77 ± 0.41 (0.086)	4.79 ± 0.27 (0.056)

E was calculated according to ASTM E 1876-09 (Eq. 1) [36]. The Young modulus can be calculated as:

$$E = \left(\frac{m \cdot f_f^2}{b}\right) \cdot \left(\frac{L^3}{t^3}\right) \cdot T_1 \qquad (1)$$

where *m* is the mass of the specimen in kg, *b*, *L* and *t* are respectively the width, the length and the thickness of the specimen in meter and the constant T_1 is the correlation factor for fundamental flexural mode to account for finite thickness and Poisson's ratio of the specimen.

2.4.2. Monotonic tensile tests at room temperature

Some of the samples FE0 and FE45 used previously for impulse excitation measurements were selected to do monotonic tensile tests at ambient laboratory conditions. These tests were performed following ISO 527-4 and ASTM D3039. The tensile tests were performed using an Instron model LM-U150 electromechanical testing machine, equipped with a 150 kN load cell and connected to a 50 mm extensometer to register the strain during the test. A crosshead speed of 2 mm/min was used. Five tests specimens were used for each composite.

2.4.3. Flexural testing at room temperature

The FEF samples used previously for acoustic test were subjected to bending test. Three-point bending was carried out using also Instron model LM-U150 equipped with a 10 kN load cell (because the specimens requires a much lower value of force in order to perform this test) and coupled with bending fixtures rolling supports. A crosshead speed was maintained at 1.5 mm/min whereas the span length (*L*) was 80 mm. The loading noses and supports were equipped with cylindrical contact surfaces of 5 mm radius. The applied load *F* and the mid-span deflection *S* data were acquired by data-acquisition system. The normal stress σ, the normal strain ε and the Young modulus are calculated according to ISO14125 and ASTM D790. The formula of flexural stress and flexural strain are given by:

$$\sigma = \frac{3FL}{2bt^2} \qquad (2)$$

$$\varepsilon = \frac{6St}{L^2} \qquad (3)$$

where *b* and *t* are respectively the width and the thickness of the specimen in mm.

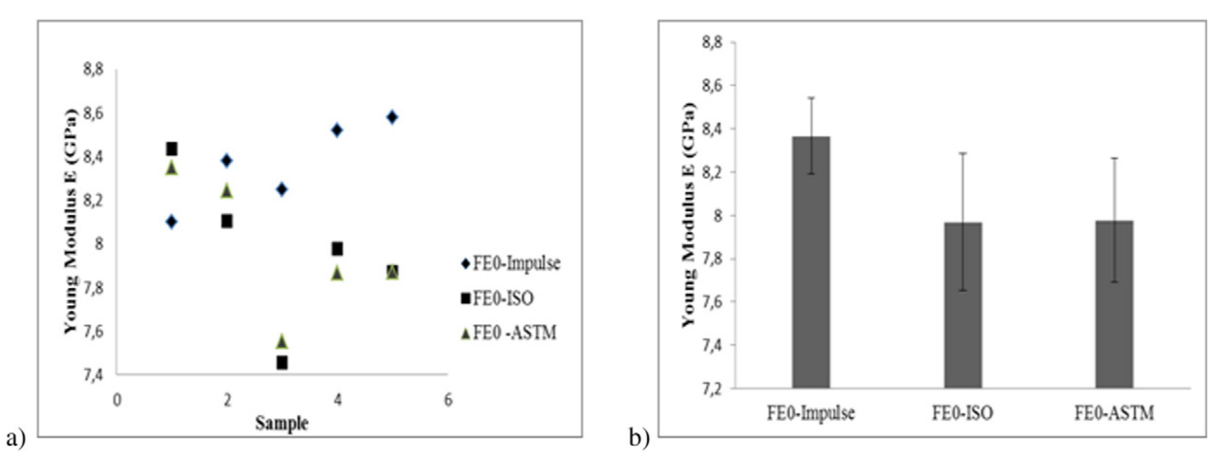

Fig. 4. Young's Modulus values of FE0 samples (a) mean value of Young's modulus (b) obtained by acoustic impulse and tensile tests.

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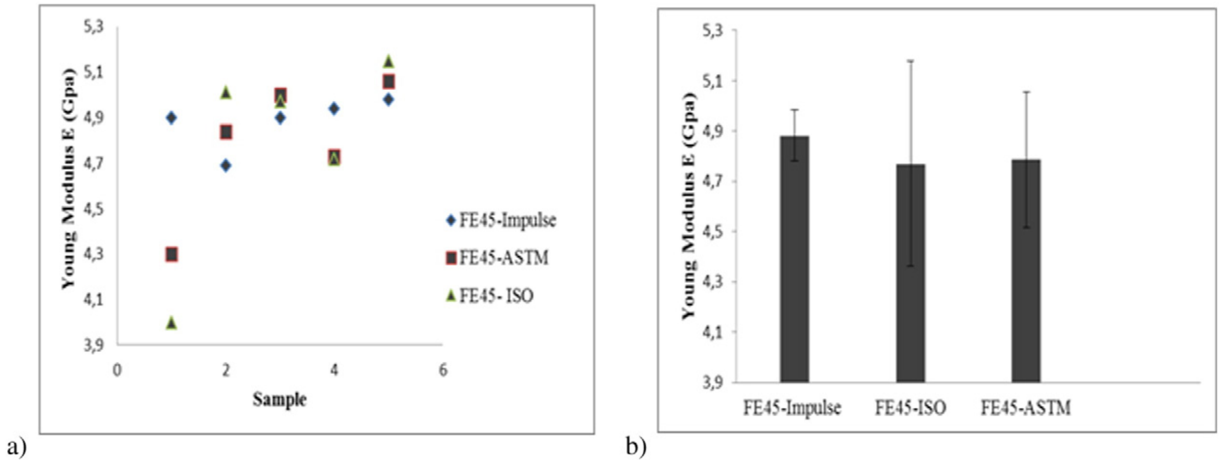

Fig. 5. Young's Modulus values of FE45 samples (a) and mean value of Young's modulus (b) obtained by acoustic impulse and tensile tests.

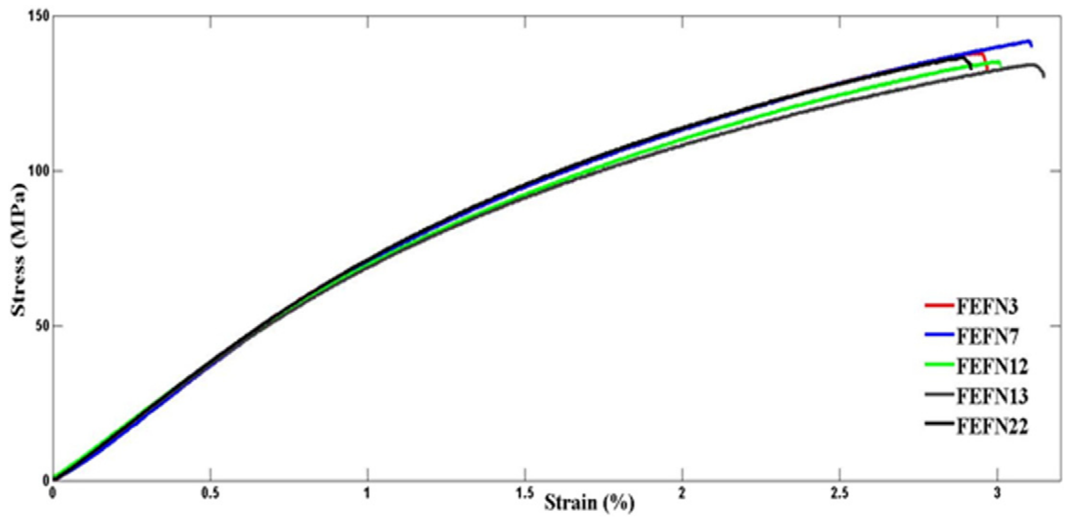

Fig. 6. Three-point bending: stress–strain curves of FEF samples obtained from three-point bending.

3. Results

3.1. Acoustic impulse

A summary of the mechanical properties recorded by RFDA is presented in Table 4. Each value is an average of five measurements and the coefficient of variation (C_v) is also shown. The low density of the specimen compared with the theoretical value is due probably to the formation of voids in the samples during the compaction process. The resonant frequency for each specimen is identified using the spectra of two strike modes: flexural and torsional vibration analysis modes.

After the fundamental frequency of each sample has been determined, ASTM E 1876-09 [36] standard method is used to calculate the Young modulus (Eq. 1). The uncertainty arising in the modulus results is partly due to the material intrinsic variability and to the systematic interference with the environment. Despite the fact that FE0 and FEF have the weft orientation and same density, it is observed that their Young moduli are different.

3.2. Monotonic tensile test

The evolution of the stress versus strain curves is shown in Fig. 3. Both types of tested specimens first go through a linear elastic phase characterized by an elastic modulus E. Then, the curve loses its initial linearity (damage of the composite is started). In the last phase the specimen finds a linear behavior up to its final rupture.

The difference in behavior between the two types of specimens FE0 and FE45 in the last step or change in the slope of the stress/strain curve (the non-linearity) is very important to their rupture [37]. This nonlinearity is due to damage of the composite and viscoelastic behavior of the epoxy matrix. The summary of results for the tensile tests is shown in Table 5. Figs. 4 and 5 show the different values of Young modulus for each specimen for FE0 and FE45 respectively and uncertainty obtained by tensile and acoustic impulse tests. It can observe the difference between the Young Modulus given by each technique. The average Young modulus in acoustic impulse test is greater than that of the tests using ASTM or ISO standards.

Table 6
Flexural characteristics of FEF samples.

Sample	Density (g/cm^3)	E-ASTM (GPa) (C_V)	E-ISO (GPa) (Cv)	σ_R (MPa)	ε_r (%)
FEF	1.12	7.73 ± 0.11 (0.014)	7.63 ± 0.19 (0.025)	136.98 ± 2.38	3.03 ± 0.08

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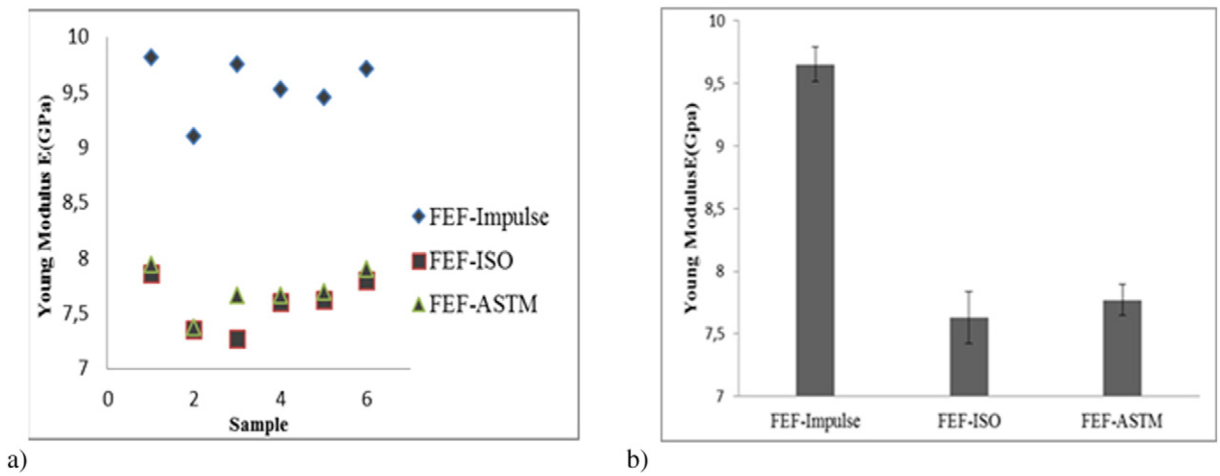

Fig. 7. Flexural modulus values of FEF samples (a) and mean value of tensile modulus (b) obtained by acoustic impulse and three point bending.

Table 7
Values of Young Modulus obtained from the different techniques.

Sample	Acoustic impulse (CV)	Tensile (CV)		Flexural (CV)	
	ASTM E 1876-09	ISO 527-5	ASTMD3039	ISO 14125	ASTMD790
FE0	8.37 ± 0.18 (0.021)	7.97 ± 0.32 (0.040)	7.98 ± 0.28 (0.036)	–	–
FEF	9.65 ± 0.14 (0.014)	–	–	7.73 ± 0.11 (0.014)	7.63 ± 0.19 (0.025)
FE45	4.88 ± 0.10 (0.020)	4.77 ± 0.41 (0.086)	4.79 ± 0.27 (0.056)	–	–

3.3. Three-point bending test

Fig. 6 shows stress–strain curves of the FEF specimens obtained from the flexural test. The same linear–nonlinear behavior observed earlier for FE0 in Fig. 3 is also observed here. This could mean that the rupture mechanism in the tensile test is similar to the one in flexural test. Compared to Fig. 3 however, the flexural strain is larger than the tensile strain.

The characteristics of the sample in bending are summarized in Table 6. It can be observed that the elasticity modulus values obtained by acoustic impulse tests (Table 4) are greater (close to 2 GPa) than those obtained by the three-point bending tests.

The flexural test is influenced by the anisotropy in the composite material, particularly the proprieties of the specimen close to the top and bottom surfaces. In our case it seems that this influence was not very significant since the Young's modulus of FEF samples tested by three-point bending was only a little lower than those of the FE0 samples tested by tensile. This difference is probably due to the shear deflections and the different ply stacking sequences [10]. Similar results were also observed by Poilane et al. [38]. Again here the modulus values obtained by the impulse test are greater than those obtained by three point bending technique (Fig. 7). It can be observed that E-ASTM and E-ISO for the flexural test are close while the E-Impulse is systematically larger.

3.4. Discussions

Table 7 represents the mean values and the variation of Young's modulus obtained by different experimental techniques and different samples. It clearly shows that the Young's modulus mean values determined by acoustic impulse techniques are typically higher than those determined by static methods (tensile and three point bending). The same observations were previously reported by Sabbagh et al. [39]. The high value of Young modulus for acoustic impulse tests is attributed

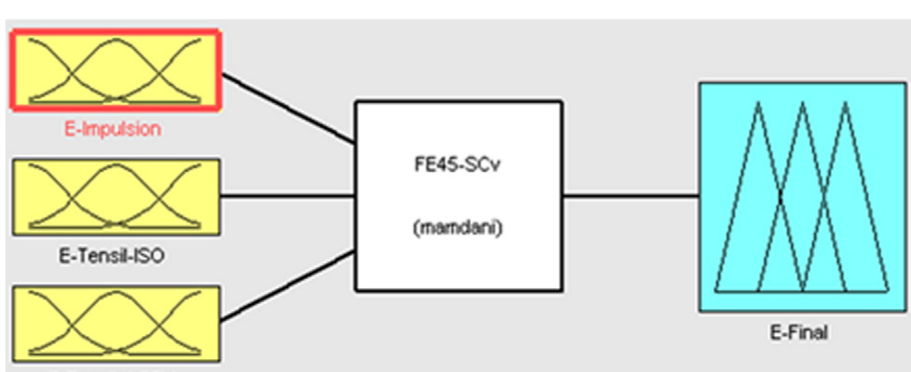

Fig. 8. Generic format of the inputs and output of the mean fuzzy model.

Table 8
Some results of mean model for FE45 samples.

$E_{Impulse}$ (GPa)	E_{ISO} (GPa)	E_{ASTM} (GPa)	E-final (GPa)	E-Mean (GPa)
4.88 (average)	4.78 (average)	4.79 (average)	4.78	4.82
4.79 (small)	4.36 (small)	4.52 (small)	4.57	4.56
4.79 (small)	4.78 (average)	5.06 (large)	4.85	4.88
4.79 (small)	4.78 (average)	4.52 (small)	4.72	4.70
4.98 (large)	5.18 (large)	5.06 (large)	5.03	5.07

to the high strain rate applied on the specimen during testing [39,40]. In the case of FEF and FE0 samples, the values of the Young's modulus of tensile and flexural tests are close to each other. But a significant difference exists between mean values of impulse tests. Indeed, the elastic proprieties of dynamic tests are very sensitive to a number of factors (mass, geometry and form of sample, surface roughness, etc.). Acoustic impulse is particularly more sensitive to the thickness of the specimen [20]. This difference of the thickness could be directly influenced the large number of vibrational modes (so called degenerative modes) and the resonant spectra in the material [20]. In addition, the porosity and the heterogeneity of the samples vary significantly from sample to sample and this random variation of the voids in each sample can certainly influence the values of Young's Modulus. The presence of voids is unavoidable and is a result of the layer stacking process. These results show the limitation of the acoustic impulse technique in giving reliable values of elastic proprieties of the tested samples. The difficulty to use dynamic resonance instrument to measure the mechanical proprieties for heterogeneous material (and fiber composite material in particularly) has been reported previously [41,42]. On the other hand, it is interesting to note the strong uncertainty of the tensile test results compared with the lower uncertainty of the acoustic impulse test. This observation is in good agreement with the results obtained by Radovic and al [20].

Because of the difficulty to compare uncertainty obtained by different methods, several authors [43–45] simply compare the average of Young's moduli and use linear regression without considering the confidential interval. In Section 4 it will be shown how fuzzy logic can be used to reconcile the values of Young's modulus by considering the coefficients of variation obtained with the different testing methods.

4. Fuzzy modeling

4.1. FE45 samples

4.1.1. Mean model

The different Young's modulus values obtained with different methods present a fuzziness characteristic and can therefore be quantified by FL. Fig. 8 shows the generic format of the fuzzy model when only the input mean is considered (here the “mean model” refers to a model without any reference to the variability inherent to each testing method). For FE45 sample, the fuzzy model shows three input parameters and one output parameter.

The numerical values of the Young's modulus obtained by tensile and acoustic impulse tests according to the ISO and ASTM standards are used as inputs of the fuzzy model. In particular an input modulus of elasticity is transformed into linguistic values with three fuzzy sets: small, average and large. For each type of specimen, the total range of these fuzzy sets is between the minimum and maximum value of the elastic modulus obtained for these specimens. These inputs and the output are related by nine fuzzy rules, a sample of which is shown here for acoustic impulse:

- If ($E_{Impulse}$ is small) then (E_{final} is small)
- If ($E_{Impulse}$ is average) then (E_{final} is average)
- If ($E_{Impulse}$ is large) then (E_{final} is large).

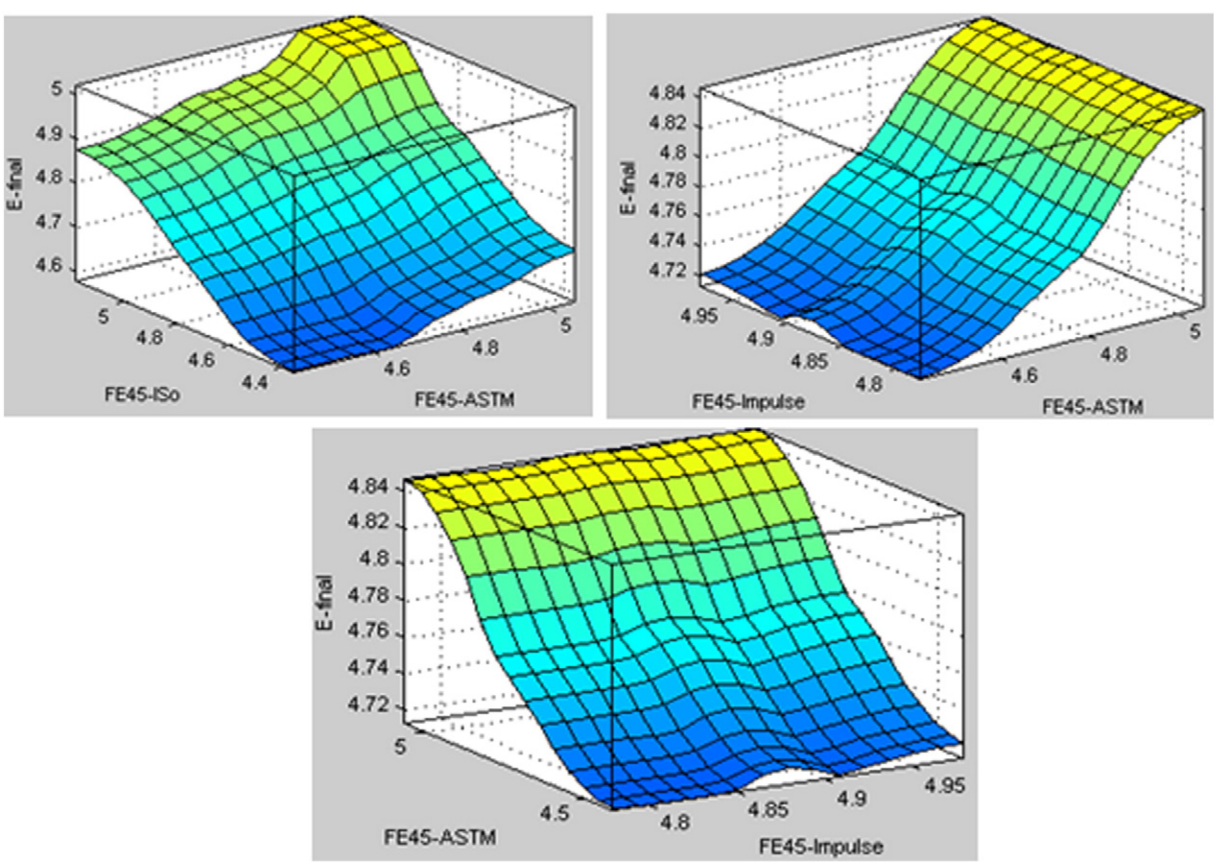

Fig. 9. Efinal surface responses, FE45 mean model.

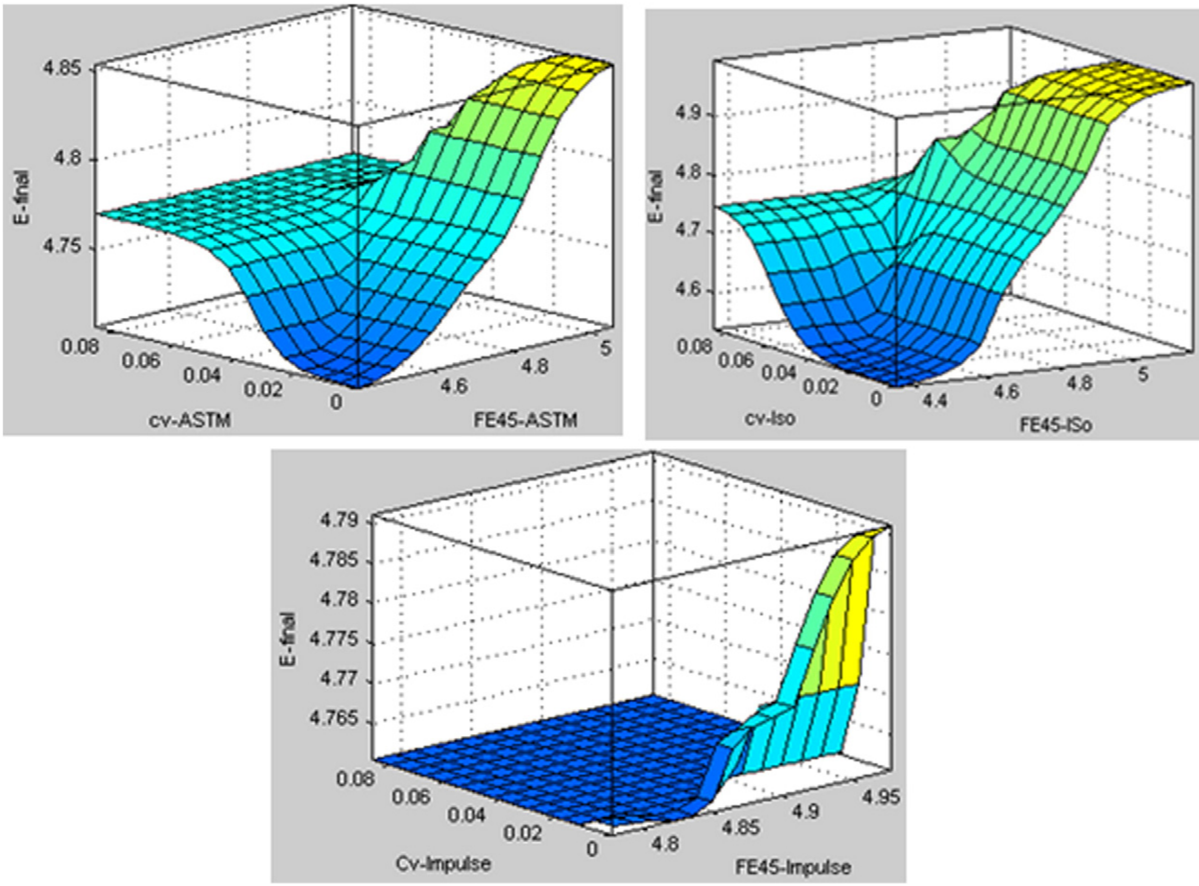

Fig. 10. E-final surface responses, FE45 mean and variation model.

The rules for tensile tests with ISO and ASTM standards are formulated similarly. The center of gravity method was used for the defuzzification process.

The statistical average of all 15 specimens using the three testing methods and standards stands at 4.82 GPa. On the other hand a value of 4.78 GPa is obtained when using the fuzzy model with all three inputs at the middle of their range, i.e. when all inputs have a 100% membership to the fuzzy set "average" (first line in Table 8). In this case it is therefore observed that the final result obtained through the fuzzy logic (E-final) differs very little from the mean value of the input variables. Other values in Table 8 show other combinations of inputs. For all combinations it can be observed that the E-final computed by the fuzzy model is always very close to the mean value of all 15 specimens (E-Mean). As a conclusion there is not much difference between a fuzzy model and a statistical average model when all inputs are classified into three fuzzy sets with no consideration of the variability of each testing method.

Fig. 9 shows the E_{final} surface response as a function of a combination of two modules while the third is kept at the middle of its interval (i.e. 100% membership to its "average" fuzzy set). As expected, it can be observed that the influence of each input variable on the output variable (E-final) is limited only in the membership range where it is defined. Therefore the values for the acoustic impulse test influence the final result in a rather narrow area corresponding to the smaller interval in which the values of this test belong. This influence is also of a rather small magnitude. On the other hand both tensile tests span a larger interval and their interactions are therefore effective in pretty much the whole range of values.

Table 9
Some results of the mean and variation fuzzy model for FE45 sample.

$E_{Impulse}$ (GPa)	E_{ISO} (GPa)	E_{ASTM} (GPa)	E-final (GPa)	E-Mean (GPa)
4.88 (++)	4.78 (−)	4.79 (−)	4.88	4.82
4.79 (++)	4.36 (−)	4.52 (−)	4.8	4.56
4.79 (++)	4.78 (−)	5.06 (−)	4.82	4.88
4.79 (++)	4.78 (−)	4.52 (−)	4.82	4.69
4.98 (++)	5.18 (−)	5.06 (−)	4.95	5.07
4.88 (−)	4.78 (++)	4.79 (−)	4.77	4.82
4.88 (−)	4.78(−)	4.79 (++)	4.79	4.82

(++) = more confidence; (−) = less confidence.

4.1.2. Mean and variation model

4.1.2.1. Output behavior for each method. The idea here is to reconcile Young's modulus by not only looking at the mean values obtained from different testing methods but by also looking at the coefficient of variation (C_v) inherent to each method, hence giving more "confidence" to inputs that present less variability (lower values of C_v). The fuzzy logic model described in Section 4.1.1 was therefore modified to include the values of the coefficient of variation (C_v) for each test as new inputs, yielding a new fuzzy model with 6 inputs and one output. The membership functions used to define the C_v of each testing method is a sigmoid function. The outputs are related by nine rules, a sample of which is shown here for acoustic impulse:

- If ($E_{Impulse}$ is small) and ($C_{v\text{-}Impulse}$ is small) then (E_{final} is small)
- If ($E_{Impulse}$ is average) and ($C_{v\text{-}Impulse}$ is small) then (E_{final} is average)
- If ($E_{Impulse}$ is large) and ($C_{v\text{-}Impulse}$ is small) then (E_{final} is large).

Similar rules were defined for the tensile ASTM samples and ISO samples.

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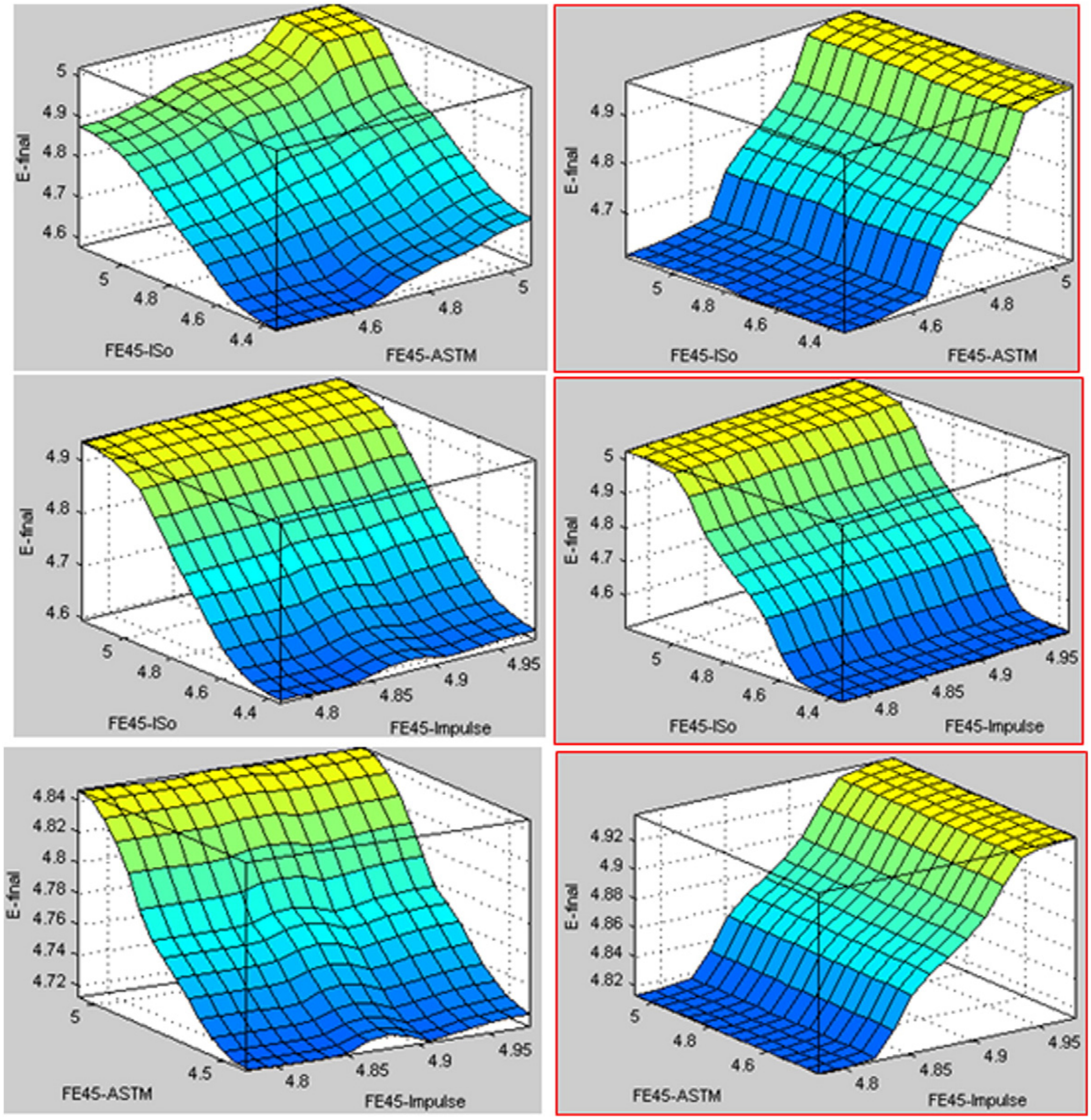

Fig. 11. Comparison between E-final surface response obtained from FE45, mean model (left) and variation model (right).

Fig. 10 shows the E_{final} surface response as a function of the modulus and coefficient of variation of each type of test (all other values are kept at the middle of their intervals). For each type of test one can clearly see how its influence on the final value vanishes when its corresponding C_v increases. For example, as soon as the C_v reaches the middle of its interval then the influence of the acoustic impulse test value disappears (recall that all other values are kept at the middle of their intervals in this particular case, this behavior can of course change if the other variables are kept at different values).

4.1.2.2. Output behavior for combined methods. Table 9 presents some combinations of each C_v values in their membership range (more confidence, less confidence, no confidence). In this case it can be seen that the E_{final} values returned by the model are dragged towards the input which has a lower C_v (i.e. more confidence), for whatever combination of inputs used. It is interesting to note that the output values (E-final) of the first five rows in Table 9 are very different from those obtained without the inclusion of coefficients of variation in Table 8.

Table 10
Some results of the mean fuzzy model for FE0 and FEF samples.

$E_{FE0-ASTM}$ (GPa)	$E_{FE0-ISO}$ (GPa)	$E_{FE0-Impulse}$ (GPa)	$E_{FEF-ASTM}$ (GPa)	$E_{FEF-ISO}$ (GPa)	$E_{FEF-Impulse}$ (GPa)	E-final (GPa)	E-Mean-FE0	E-Mean-FEF	E-Mean (GPa)
7.98 (average)	7.97 (average)	8.37 (average)	7.73 (average)	7.63 (average)	9.65 (average)	8.21	8.11	8.34	8.22
7.7 (small)	7.65 (small)	8.19 (small)	7.62 (small)	7.44 (small)	9.51 (small)	8.02	7.85	8.19	8.02
7.7 (small)	7.65 (small)	8.19 (small)	7.84 (large)	7.82 (large)	9.72 (large)	8.29	7.85	8.46	8.15
8.26 (large)	8.29 (large)	8.55 (large)	7.62 (small)	7.44 (small)	9.51 (small)	8.20	8.37	8.19	8.28
8.26 (large)	8.29 (large)	8.55 (large)	7.84 (large)	7.82 (large)	9.72 (large)	8.41	8.37	8.46	8.41

(++) = more confidence; (–) = less confidence.

Fig. 11 shows a comparison of the E-final surface model with and without inclusion of the C_v. Different combinations of C_v values were used. In particular more confidence was given to E-ASTM for the top-right of Fig. 10, more confidence to E-ISO for the middle-right figure and more confidence to E-Impulse for the bottom-right figure. As can be seen the input modulus variable which has the smallest C_v drives completely the final response, as expected.

4.2. FE0 and FEF samples

4.2.1. Mean model

Considering that Young's modulus is not dependent on the sample thickness, it is possible to consider the three-point bending values, tensile values and acoustic impulse values in the same fuzzy model (recall that FE0 and FEF samples have the same orientation, but different thicknesses). The fuzzy mean model will therefore have 6 inputs and one output. The fuzzy rules used in the model are formulated similarly to those presented in Section 4.1.2.1.

The statistical average of all FE0 and FEF specimen stands at 8.22 GPa. On the other hand a value of 8.21 GPa is obtained when using the fuzzy model with all inputs at the middle of their range, i.e. when all inputs have a 100% membership to the fuzzy set "average" (first line in Table 10). Other combinations of inputs are also shown in Table 10. As observed earlier in Table 9, for most combinations the E-final computed by the fuzzy model is somewhat close (if not equal) to the mean value (E-Mean) reported in the last column.

Fig. 12 shows the E_{final} responses as a function of combinations of two modules while the third is kept at the middle of its interval (i.e. 100% membership to its "average" fuzzy set). It is observed that each input has an influence on the final result in the interval for which it is defined. For FEF inputs particularly, the influence of FEF-ASTM on the final result has less influence than other FEF inputs because of its smaller application interval. Similarly, a larger range is observed for FE0 sample when compared to FEF sample.

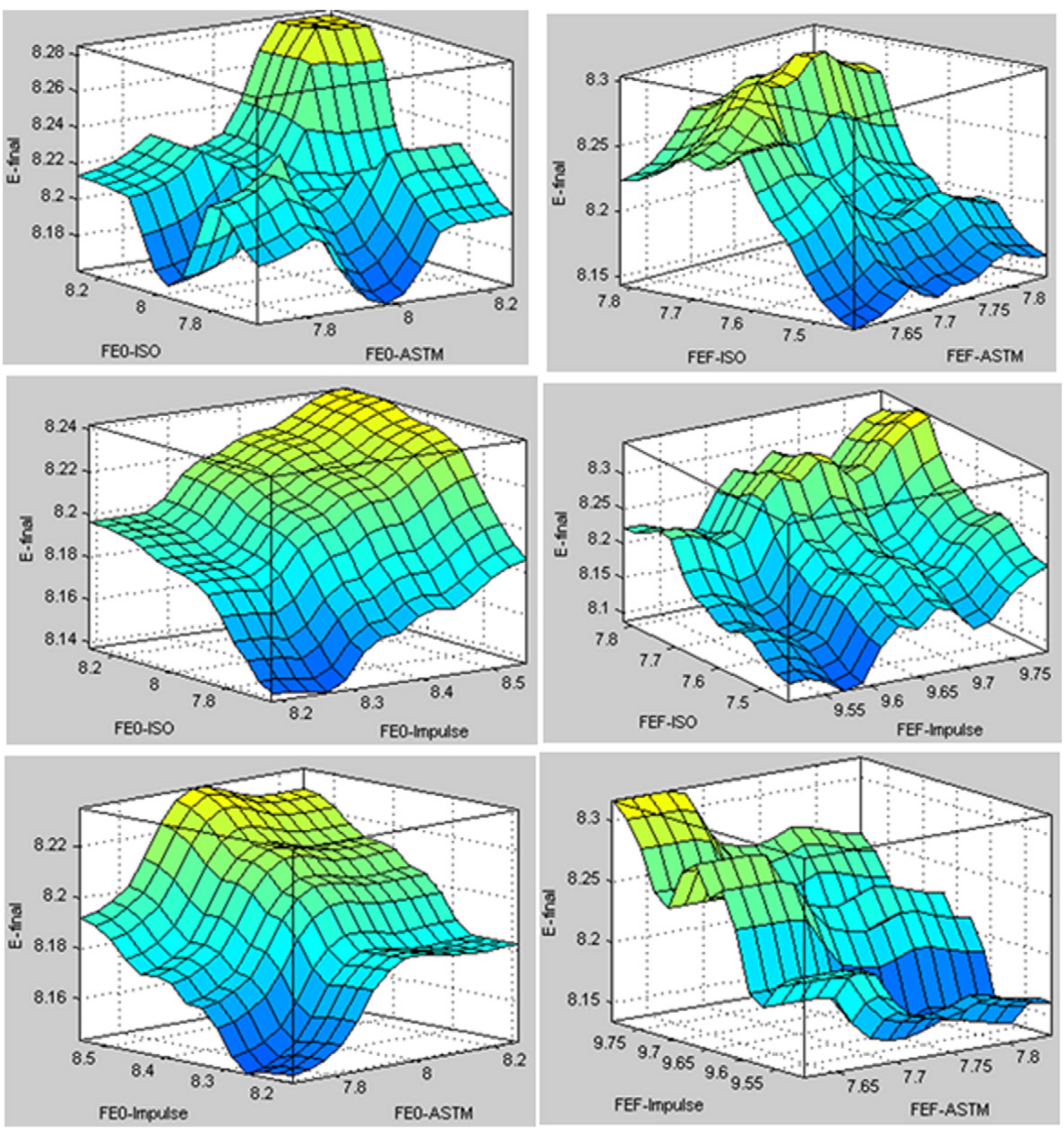

Fig. 12. E-final surface responses, FE0 and FEF, mean model.

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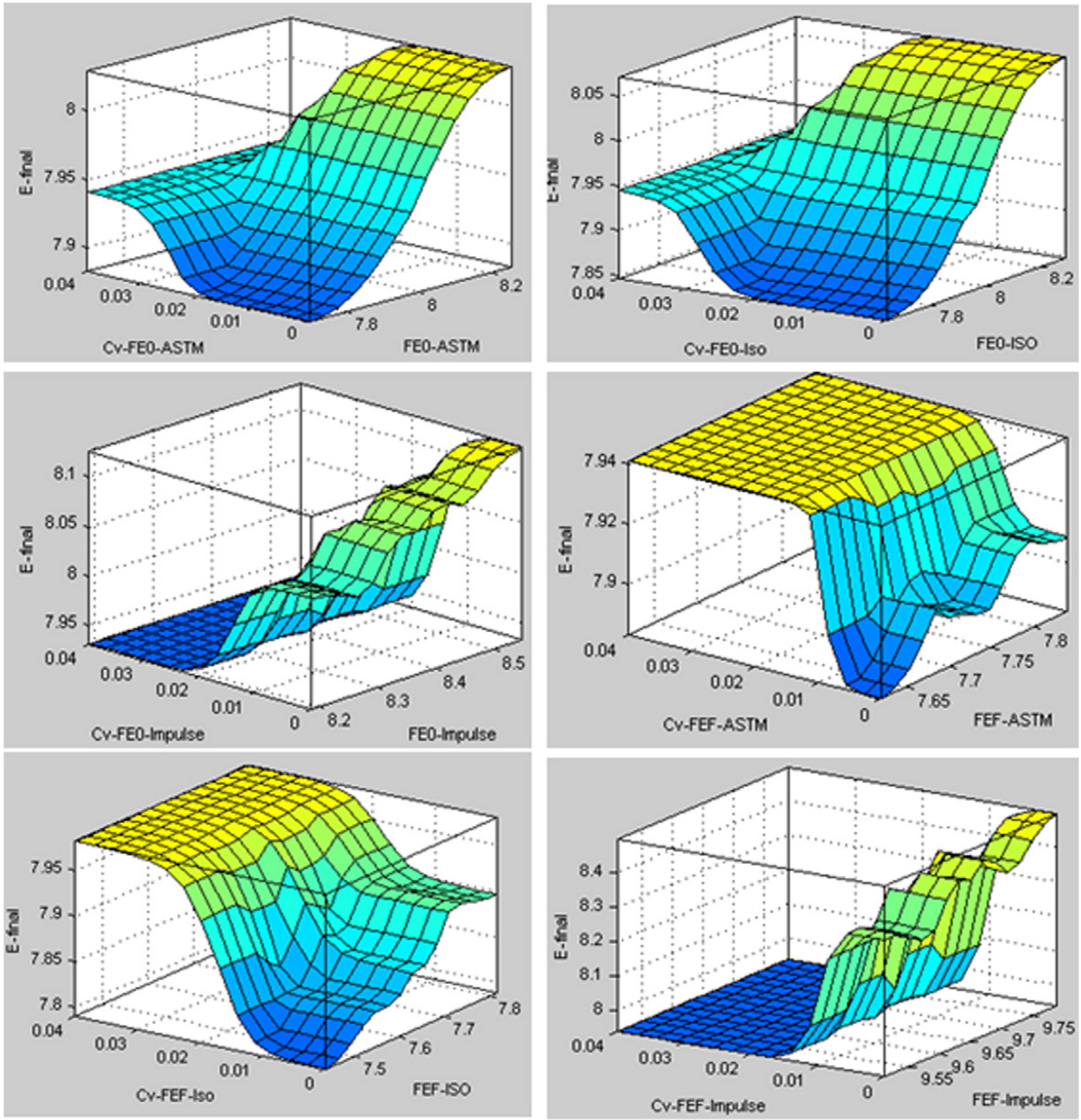

Fig. 13. E-final surface responses, FE0 and FEF mean and variation model.

4.2.2. Mean and variation model

4.2.2.1. Output behavior for each method. The fuzzy model with inclusion of C_v will now contain 12 inputs and one output. Fig. 13 shows the E-$_{final}$ response as a function of the modulus and coefficient of variation of each type of test (all other values are kept at the middle of their intervals). As was already observed for FE45 samples, the influence on the final value vanishes when the C_v increases.

4.2.2.2. Output behavior for combined methods. Table 11 presents the fuzzy results for different combinations of C_v values (more confidence, less confidence, no confidence). The fuzzy results obtained are compared with the mean value of each sample and the total average value of the samples. As can be seen the values of E-$_{final}$ are different from the statistical mean values and are once again dragged towards the variable which has smaller C_v. This is also very clear when we compare the results of the first five rows of Table 11 with the first five rows of

Table 11
Some results of the mean and variation fuzzy model for FE0 and FEF sample.

$E_{FE0\text{-}ASTM}$ (GPa)	$E_{FE0\text{-}Iso}$ (GPa)	$E_{FE0\text{-}Impulse}$ (GPa)	$E_{FEF\text{-}ASTM}$ (GPa)	$E_{FEF\text{-}ISO}$ (GPa)	$E_{FEF\text{-}Impulse}$ (GPa)	E_{final} (GPa)	E-Mean-FE0	E-Mean-FEF	E-Mean (GPa)
7.98 (−)	7.97 (−)	8.37 (−)	7.73 (++)	7.63 (−)	9.65 (−)	7.74	8.11	8.34	8.22
7.7 (−)	7.65 (−)	8.19 (−)	7.62 (++)	7.44 (−)	9.51 (−)	7.66	7.84	8.19	8.02
7.7 (−)	7.65 (−)	8.19 (−)	7.84 (++)	7.82 (−)	9.72 (−)	7.82	7.85	8.46	8.15
8.26 (−)	8.29 (−)	8.55 (−)	7.62 (++)	7.44 (−)	9.51 (−)	7.67	8.37	8.19	8.11
8.26 (−)	8.29 (−)	8.55 (−)	7.84 (++)	7.82 (−)	9.72 (−)	7.82	8.37	8.46	8.41
7.98 (++)	7.97 (−)	8.37 (−)	7.73 (−)	7.63 (−)	9.65 (−)	7.98	8.11	8.34	8.22
7.98 (−)	7.97 (++)	8.37 (−)	7.73 (−)	7.63 (−)	9.65 (−)	7.97	8.11	8.34	8.22
7.98 (−)	7.97 (−)	8.37 (++)	7.73 (−)	7.63 (−)	9.65 (−)	8.36	8.11	8.34	8.22
7.98 (−)	7.97 (−)	8.37 (−)	7.73 (−)	7.63 (++)	9.65 (−)	7.64	8.11	8.34	8.22
7.98 (−)	7.97 (−)	8.37 (−)	7.73 (−)	7.63 (−)	9.65 (++)	9.58	8.11	8.34	8.22

Table 10. Fig. 14 presents a comparison of the models with and without the Cv. Recall from Tables 4 to 6 that FEF impulse and FEF ASTM have the lowest Cv which both stand at 0.014. As expected, the models with inclusion of the Cv are different from those without. For example, the 2 models on top of Fig. 14 show how the low variability of FEF impulse drives completely the response when its CV is included in the model on the right. The same applies for FEF ASTM when its C_V is included in the middle-right and bottom-right models in Fig. 14. Clearly uncertainty plays an important role in the computation of the reconciled module value.

5. Conclusion

Three types of laminated NFC made of commercial flax–epoxy, identified by FE0, FE45 and FEF in this paper, were manufactured by thermal compression.

Samples were cut from plates and tested by a non-destructive acoustic impulse method to evaluate their Young's modulus. Destructive tensile tests and bending tests were also performed later on the same specimens to evaluate their mechanical properties in monotonic tension and monotonic three-point bending tests as per ISO and ASTM standards.

The results show a certain level of variability in the values of Young's modulus obtained by the different techniques and/or standards. It was therefore proposed to develop a model that reconciles these values rather than calculating a simple average value, in hope to obtain a more representative and reliable module that could be useful for evaluating the performance of such materials, or for further study of eventual structures that can be made from them.

Fuzzy logic was chosen as the modeling method. Continuous models of the reconciled value of the elastic modulus could be obtained that also take into consideration the variability of the measurements. In this paper such variation was included in the form of the measured coefficient of variation inherent to each test method.

The results obtained show how the model adapts simultaneously to the mean and C_v values of each type of test. Generally speaking, for any method used in this paper, a larger mean value combined with a lower C_v will result in fuzzy sets that will cover a larger portion of the defuzzified

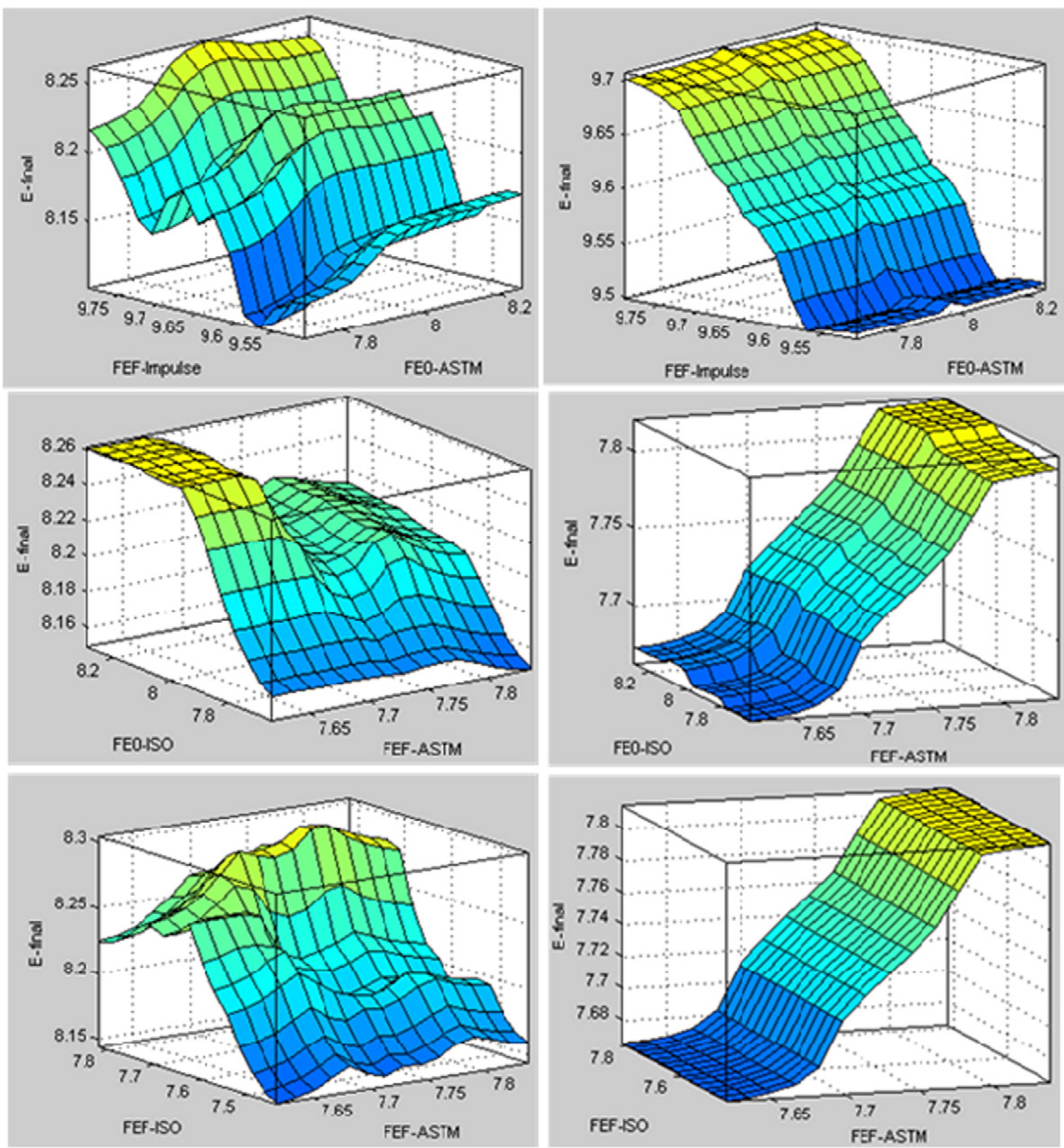

Fig. 14. Comparison between Efinal surface response obtained from FEF and FE0, mean model (left) and variation model (right).

output, hence making the "weight" of this method predominant compared to the other ones.

Future work includes building fuzzy models with larger sets of data, for example using other types of NFC or samples with different ply orientations. Further investigations could also be oriented towards the comparative study of the results obtained using different configurations of the developed fuzzy model (fuzzification methods, inference method, defuzzification method, etc.).

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References

[1] D.U. Shah, P.J. Schubel, M.J. Clifford, Can flax replace E-glass in structural composites? A small wind turbine blade case study, Compos. Part B 52 (2013) 172–181.
[2] M.R. Mansor, S.M. Sapuan, E.S. Zainudin, A.A. Nuraini, A. Hambali, Hybrid natural and glass fibers reinforced polymer composites material selection using Analytical Hierarchy Process for automotive brake lever design, Mater. Des. 51 (2013) 484–492.
[3] F. Ahmad, H.S. Choi, M.K. Park, A review: natural fiber composites selection in view of mechanical, light weight, and economic properties, Macromolecular Materials and Engineering, 2014.
[4] S.M. Bertrand Lascoup, M. Chauvin, L. Guillaumat, A.B. CheikhLarbi, Caractérisations mécaniques et identification des mécanismes d'endommagent d'un composite à fibre de lin composé de couches de papier, Presented at the JNC 18, Nantes, 2013.
[5] J. Summerscales, N. Dissanayake, A. Virk, W. Hall, A review of bast fibres and their composites. Part 2–composites, Compos. A: Appl. Sci. Manuf. 41 (2010) 1336–1344.
[6] C. Baley, Analysis of the flax fibres tensile behaviour and analysis of the tensile stiffness increase, Compos. A: Appl. Sci. Manuf. 33 (7/1/2002) 939–948.
[7] K. Charlet, J.-P. Jernot, J. Breard, M. Gomina, Scattering of morphological and mechanical properties of flax fibres, Ind. Crop. Prod. 32 (11//2010) 220–224.
[8] S. Siengchin, R. Dangtungee, Effect of woven flax structures on morphology and properties of reinforced modified polylactide composites, J. Thermoplast. Compos. Mater. 26 (2013) 1424–1440.
[9] D.U. Shah, Developing plant fibre composites for structural applications by optimising composite parameters: a critical review, J. Mater. Sci. 48 (2013) 6083–6107.
[10] Lord, R. Morrell, Elastic modulus measurement, Measurement Good Practice Guide, vol. 98, 2006.
[11] A. Ridruejo, C. González, J. Llorca, Damage micromechanisms and notch sensitivity of glass-fiber non-woven felts: an experimental and numerical study, J. Mech. Phys. Solids 58 (10//2010) 1628–1645.
[12] S.B. Chemikosova, N.V. Pavlencheva, O.P. Gur'yanov, T.A. Gorshkova, The effect of soil drought on the phloem fiber development in long-fiber flax, Russ. J. Plant Physiol. 53 (2006) 656–662 (2006/09/01).
[13] A.J. Norton, S.J. Bennett, M. Hughes, J.P.R.E. Dimmock, D. Wright, G. Newman, et al., Determining the physical properties of flax fibre for industrial applications: the influence of agronomic practice, Ann. Appl. Biol. 149 (2006) 15–25.
[14] C. Baillie, Green composites: polymer composites and the environment, Elsevier, 2004.
[15] S. Alix, E. Philippe, A. Bessadok, L. Lebrun, C. Morvan, S. Marais, Effect of chemical treatments on water sorption and mechanical properties of flax fibres, Bioresour. Technol. 100 (10//2009) 4742–4749.
[16] J. Andersons, E. Poriķe, E. Spārniņš, The effect of mechanical defects on the strength distribution of elementary flax fibres, Compos. Sci. Technol. 69 (10//2009) 2152–2157.
[17] N.M. Barkoula, S.K. Garkhail, T. Peijs, Biodegradable composites based on flax/polyhydroxybutyrate and its copolymer with hydroxyvalerate, Ind. Crop. Prod. 31 (1//2010) 34–42.
[18] D.U. Shah, P.J. Schubel, M.J. Clifford, P. Licence, The tensile behavior of off-axis loaded plant fiber composites: an insight on the nonlinear stress–strain response, Polym. Compos. 33 (2012) 1494–1504.
[19] J. Baets, D. Plastria, J. Ivens, I. Verpoest, Determination of the optimal flax fibre preparation for use in UD flax-epoxy composites, Presented At The 18th International Conference On Composite Materials, 2011.
[20] M. Radovic, E. Lara-Curzio, L. Riester, Comparison of different experimental techniques for determination of elastic properties of solids, Mater. Sci. Eng. A 368 (3/15/2004) 56–70.
[21] L. Toubal, M. Karama, B. Lorrain, Determination of the matrix of rigidity of a composite material by the combination of speckle interferometry and ultrasonic measurements, Applied Mechanics and Materials, 3–4 2005, pp. 155–160 (ed.).
[22] L.I. Raggio, J. Etcheverry, G. Sánchez, N. Bonadeo, Error analysis of the impulse excitation of vibration measurement of acoustic velocities in steel samples, Phys. Procedia 3 (1/1/2010) 297–303.
[23] H. Bohlooli, A. Nazari, G. Khalaj, M.M. Kaykha, S. Riahi, Experimental investigations and fuzzy logic modeling of compressive strength of geopolymers with seeded fly ash and rice husk bark ash, Compos. Part B 43 (4//2012) 1293–1301.
[24] Z.L. Askar, Fuzzy set, Inf. Control. 8 (1965) 353.
[25] M. E. H., Application of fuzzy algorithms for control of simple dynamic plants, Proc. IEEE 121 (1976) 1585–1588.
[26] F. Demir, A new way of prediction elastic modulus of normal and high strength concrete—fuzzy logic, Cem. Concr. Res. 35 (8//2005) 1531–1538.
[27] N. Ali, D. Neda, Analytical investigations and fuzzy logic-based modeling of the impact resistance of aluminum–epoxy laminated composites, SCIENCE CHINA Technol. Sci. 54 (2011) 2785–2794.
[28] F. Yapici, A. Ozcifci, T. Akbulut, R. Bayir, Determination of modulus of rupture and modulus of elasticity on flakeboard with fuzzy logic classifier, Mater. Des. 30 (6//2009) 2269–2273.
[29] Y.F. Han, W.D. Zeng, Y.Q. Zhao, Y. Sun, X. Ma, A study on the prediction of mechanical properties of titanium alloy based on adaptive fuzzy-neural network, Mater. Des. 32 (6//2011) 3354–3360.
[30] M. Tajdari, A. Ghaffarnajad Mehraban, A.R. Khoogar, Shear strength prediction of Ni–Ti alloys manufactured by powder metallurgy using fuzzy rule-based model, Mater. Des. 31 (3//2010) 1180–1185.
[31] W. Yu, M.Q. Li, J. Luo, S. Su, C. Li, Prediction of the mechanical properties of the post-forged Ti–6Al–4V alloy using fuzzy neural network, Mater. Des. 31 (8//2010) 3282–3288.
[32] M. Zare, J. Vahdati Khaki, Prediction of mechanical properties of a warm compacted molybdenum prealloy using artificial neural network and adaptive neuro-fuzzy models, Mater. Des. 38 (6//2012) 26–31.
[33] İ.B. Topçu, C. Karakurt, M. Sarıdemir, Predicting the strength development of cements produced with different pozzolans by neural network and fuzzy logic, Mater. Des. 29 (12//2008) 1986–1991.
[34] P. Jaganathan, Sivasubramanian, V. Krishnaraj, Experimental investigation of surface roughness and tool life in hard turning of AISI M2 steel using CBN insert, International Review of Mech. Eng. 8 (2014) 174–189.
[35] N.K. Sharma, V. Kumar, Studies on properties of banana fiber reinforced green composite, J. Reinf. Plast. Compos. 32 (2013) 525–532.
[36] A. E. 1876–09, Standard Test Method for Dynamic Young's Modulus, Shear Modulus, and Poisson's Ratio by Impulse Excitation of Vibration," (ed), 2000.
[37] L. Toubal, G. Lebrun, "Nouvelle méthode de fabrication des composites a fibres naturelles: Contribution d'une couche de papier à minimiser la disparité des propriétés mécaniques," presented at the JNC 17, Poitiers (France), 2011.
[38] A.V. Christophe Poilâne, L. Momayez, Propriétés mécaniques de préimprégnés lin/époxyde, Presented at the JNC 16, Toulouse, Toulouse (France), 2009.
[39] J. Sabbagh, J. Vreven, G. Leloup, Dynamic and static moduli of elasticity of resin-based materials, Mater. Des. 18 (1//2002) 64–71.
[40] J. Leprince, W.M. Palin, T. Mullier, J. Devaux, J. Vreven, G. Leloup, Investigating filler morphology and mechanical properties of new low-shrinkage resin composite types, J. Oral Rehabil. 37 (2010) 364–376.
[41] D. Breysse, Nondestructive evaluation of concrete strength: an historical review and a new perspective by combining NDT methods, Constr. Build. Mater. 33 (2012) 139–163.
[42] L.I. Raggio, J. Etcheverry, G. Sánchez, N. Bonadeo, Error analysis of the impulse excitation of vibration measurement of acoustic velocities in steel samples, Physics Procedia 2010, pp. 297–303.
[43] J.M.L.D.W. Haines, C. Herbe, Determination of Young's modulus for spruce, fir and isotropic materials by the resonance flexure method with comparisons to static flexure and other dynamic methods, Wood Sci. Technol. 30 (1996) 253–263.
[44] N.L. Batista, K. Iha, E.C. Botelho, Evaluation of weather influence on mechanical and viscoelastic properties of polyetherimide/carbon fiber composites, J. Reinf. Plast. Compos. 32 (//2013) 863–874.
[45] R.R.J.R.F. Pellerin, Nondestructive evaluation of wood, Forest Products Society ed., 2002.