An Improved Method for Identification of the Interfacial Shear Strength by Tensile Tests of Short-Fiber Composites

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Introduction

- Tests to characterize interfacial shear strength:
  - Single fiber fragmentation test
  - Fiber pull-out test
  - Micro-droplet test
- Common issues are:
  - Difficult to perform
  - Skewed results due to selective tests
  - Different stress state (model composite tests)

Objectives

The main objective of this study is to develop and validate indirect, more ***industry-friendly methodology*** for characterization of interfacial shear strength (IFSS)

Theory

Stress as a function of strain in short fiber composite

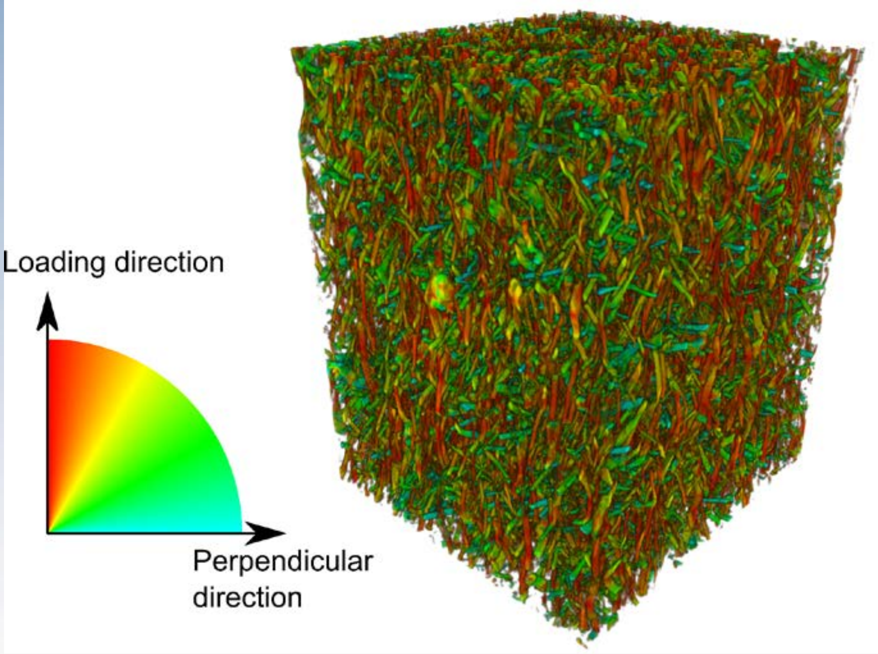
$$\sigma_c = \eta_o \eta_l v_f E_f \varepsilon + \left(1 - v_f\right)\sigma_m$$

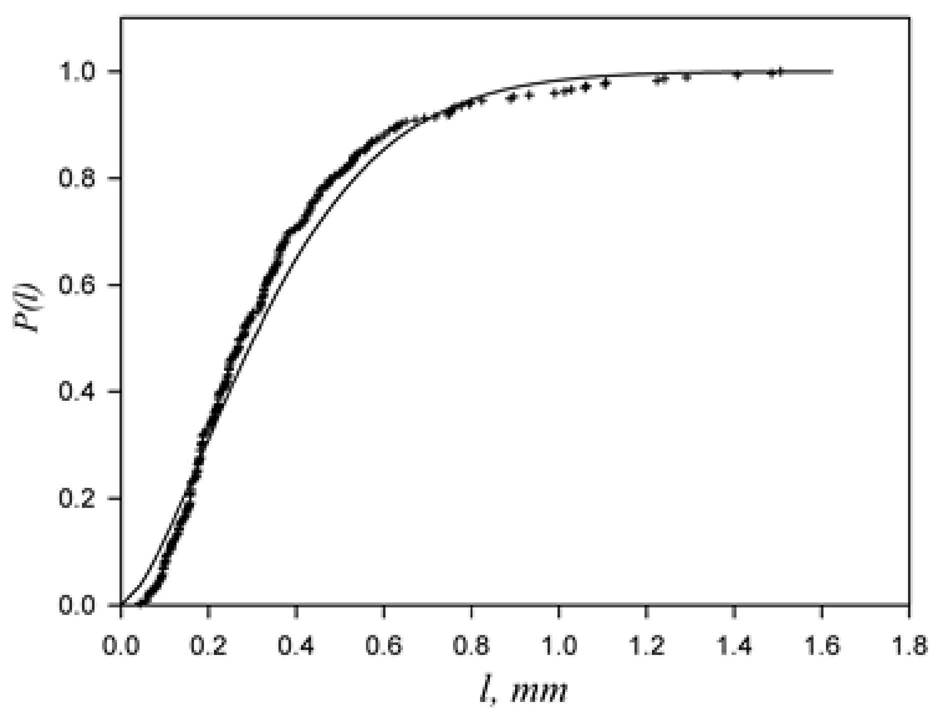
η_o	fiber orientation factor
η_l	fiber length efficiency factor
v_f	fiber volume fraction
E_f	longitudinal modulus of linear elastic reinforcing fibers

$$\sigma_m = \sigma_m\left(\varepsilon\right)$$

axial stress acting in the matrix, the nonlinear deformation of matrix and the inelastic **stress transfer** between the constituents may be responsible for the non-linearity of the composite

Theory: Fiber length efficiency factor





$$\eta_l = \frac{1}{\langle l \rangle} \int_0^\infty \eta_l^*(l) l p(l) dl$$

Theory: η_l, linear elastic case

$$\eta_l^*(l) = 1 - \frac{\tanh \beta l/2}{\beta l/2} \qquad \beta = \frac{2}{r_f}\sqrt{\frac{2G_m}{E_f \ln\left(\pi/2\sqrt{3}\nu_f\right)}}$$

$$\tau = -\frac{E_f \varepsilon \beta r_f}{2}\frac{\sinh \beta x}{\cosh \beta l/2} \qquad \sigma_f = E_f \varepsilon\left(1 - \frac{\cosh \beta x}{\cosh \beta l/2}\right)$$

Where r_f designates the fiber radius and β is the shear lag parameter, G_m denoting the shear modulus of matrix.

Theory: η_l, elastic-plastic stress transfer

$$\eta_l^*(l)=\begin{cases} 1-\dfrac{\tanh \beta l/2}{\beta l/2} & l\le l_{el} \\ 1-\left(1-\dfrac{2\tau_i l_p}{E_f \varepsilon r_f}\right)\dfrac{\tanh \beta\left(l/2-l_p\right)}{\beta l/2}-\dfrac{2l_p}{l}\left(1-\dfrac{\tau_i l_p}{E_f \varepsilon r_f}\right) & l>l_{el} \end{cases}$$

$$l_{el}=\frac{2}{\beta}\tanh^{-1}\frac{2\tau_i}{E_f \varepsilon \beta r_f} \qquad \coth \beta\left(l/2-l_p\right)+\beta l_p=\frac{E_f \varepsilon \beta r_f}{2\tau_i}$$

Theory: η_l, rigid-perfectly plastic stress transfer

$$\eta_l^*(l) = \begin{cases} \dfrac{l}{2l_c} & l \le l_c \\[2ex] 1 - \dfrac{l_c}{2l} & l > l_c \end{cases}$$

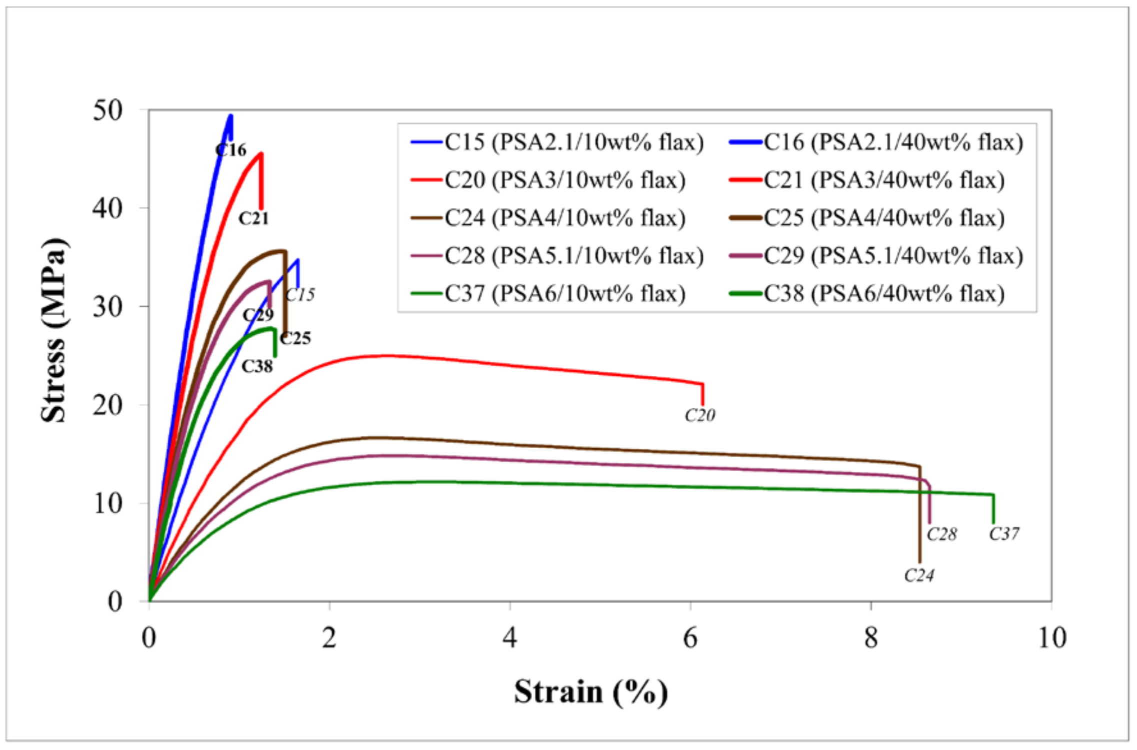
$$l_c = \frac{E_f \varepsilon}{\tau_i} r_f$$

$$P(l) = 1 - \exp\left[-\left(\frac{l}{l_W}\right)^{\alpha}\right]$$

$$\eta_l = \frac{\Gamma\left(1+\dfrac{1}{\alpha}, \left(\dfrac{l_c}{l_W}\right)^{\alpha}\right) + \dfrac{l_W}{\alpha\, l_c}\left[\Gamma\left(\dfrac{2}{\alpha}\right) - \Gamma\left(\dfrac{2}{\alpha}, \left(\dfrac{l_c}{l_W}\right)^{\alpha}\right)\right] - \dfrac{l_c}{l_W}\exp\left[-\left(\dfrac{l_c}{l_W}\right)^{\alpha}\right]}{\Gamma\left(1+\dfrac{1}{\alpha}\right)}$$

Theory: orientation factor

$$E_c = \eta_o \eta_l E_f \nu_f + (1-\nu_f) E_m \qquad \eta_o = \left(E_c - (1-\nu_f)E_m\right) / \eta_l E_f \nu_f$$



η_o is obtained from linear part of the σ–ε curve

IFSS is obtained by fitting the **whole σ–ε curve**

Experimental: materials

The flax fibers were supplied by Ekotex, Poland, and an amylose-rich corn starch was obtained from Gargill, USA (Cerestar Amylogel 03003: 65 wt% amylose and 35 wt% amylopectin).

Fibers were pelletized, compound mixed in twin screw extruder and specimens produced by injection molding.

Compounds with different contents of fibers (10 wt%, 40 wt%) and plasticizer (20 wt%, 25 wt%, 32.5 wt%, 35 wt%).

Experimental: tensile test

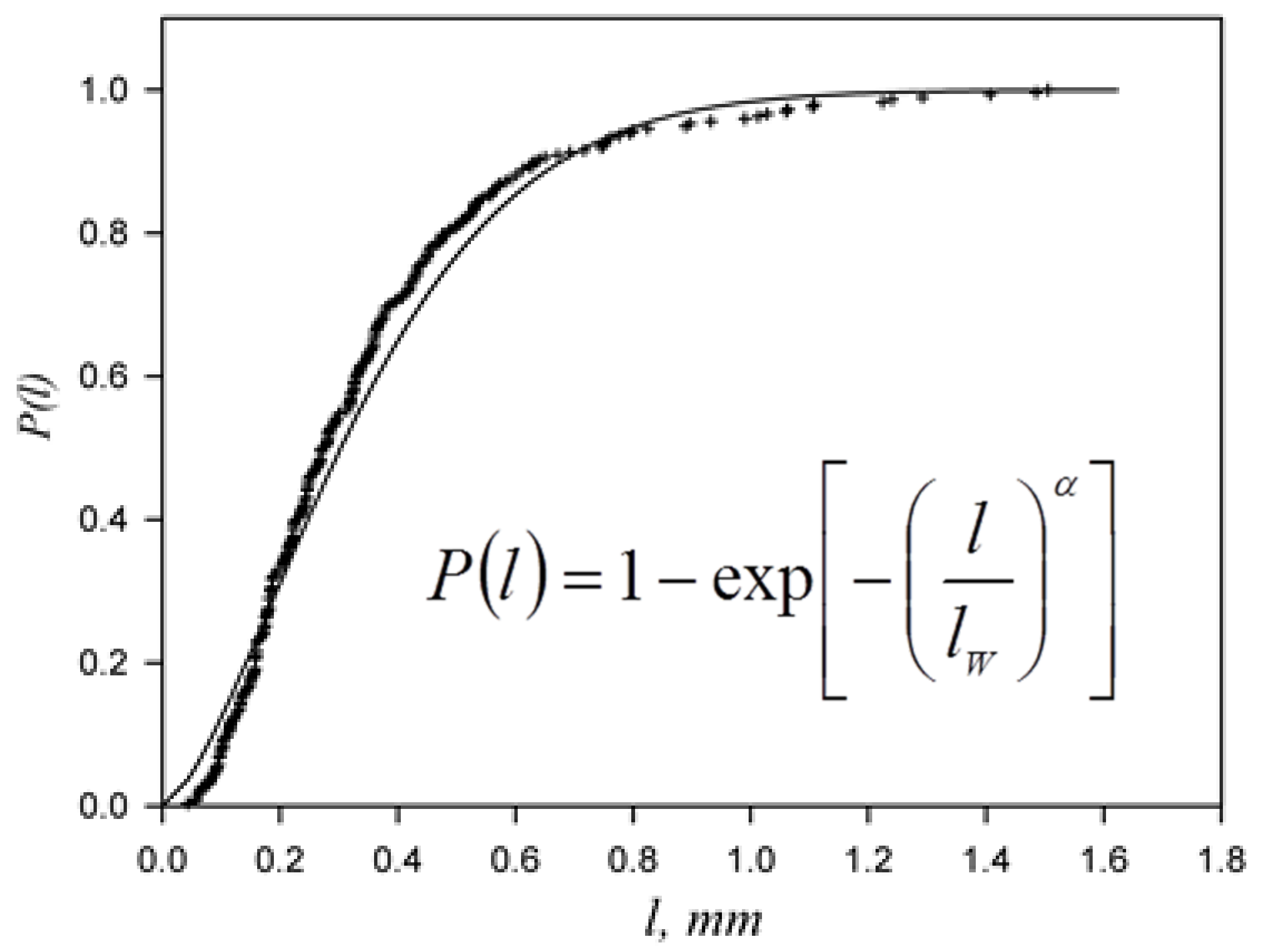
Tensile properties were measured according to the ISO 527 standard by using an Instron 4505 Universal Tensile Tester with 10 kN load cell. Test carried out at 5 mm/min cross-head speed, strain was measured by an Instron 2665 Series High Resolution Digital Automatic Extensometer.

At least 5 dog-bone shaped were tested for each composite.

Testing was performed at controlled ambient conditions at 23ºC and relative humidity of 50%.

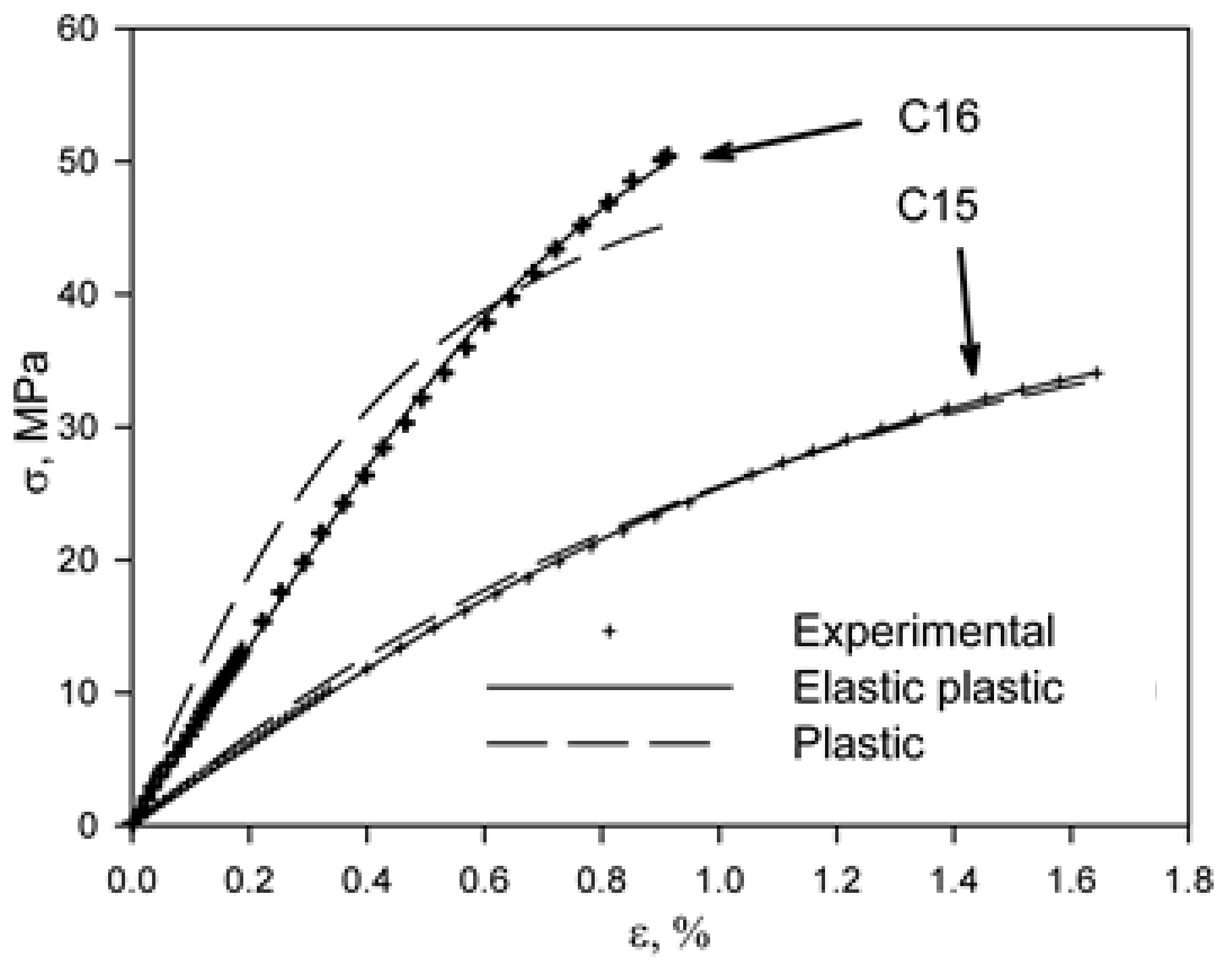
Fiber length distribution was obtained by optical microscopy on fibers extracted from composites.

Results and Discussion



$$P(l) = 1 - \exp\left[-\left(\frac{l}{l_W}\right)^{\alpha}\right]$$

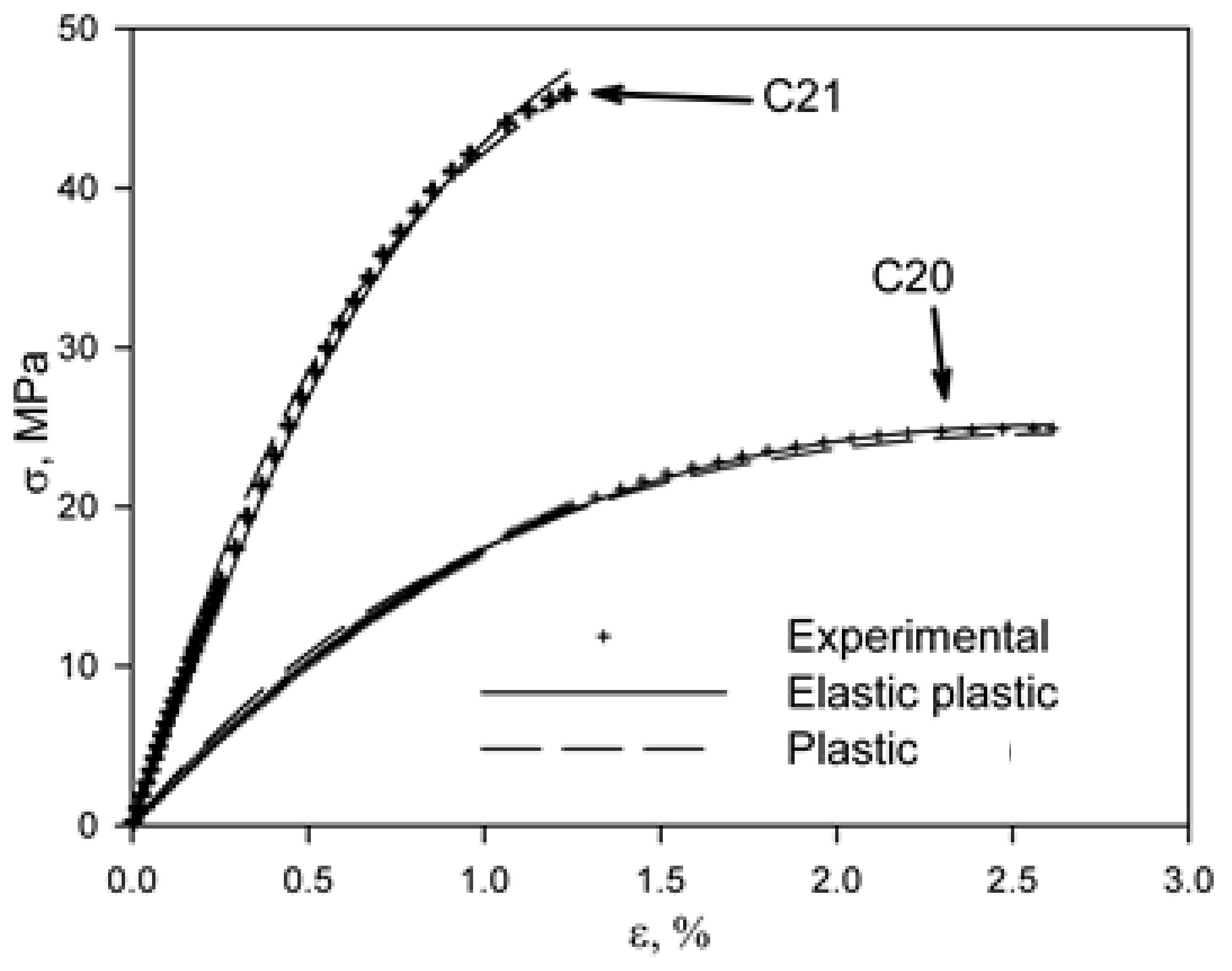
Results and Discussion



Flax/PSA

wt. %	Plast.	v_f
C15	20	10
C16	20	40

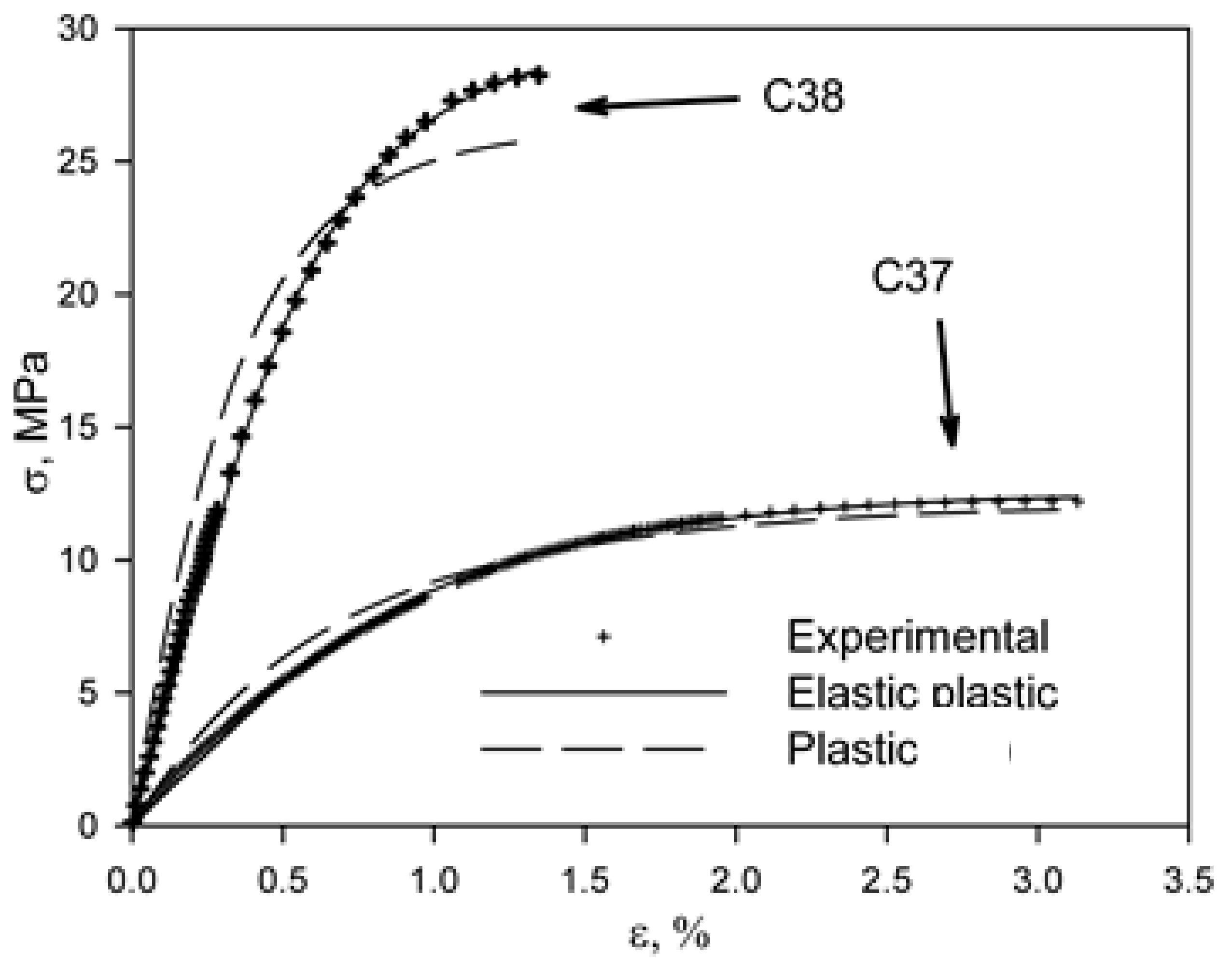
Results and Discussion



Flax/PSA

wt. %	Plast.	v_f
C20	25	10
C21	25	40

Results and Discussion



Flax/PSA

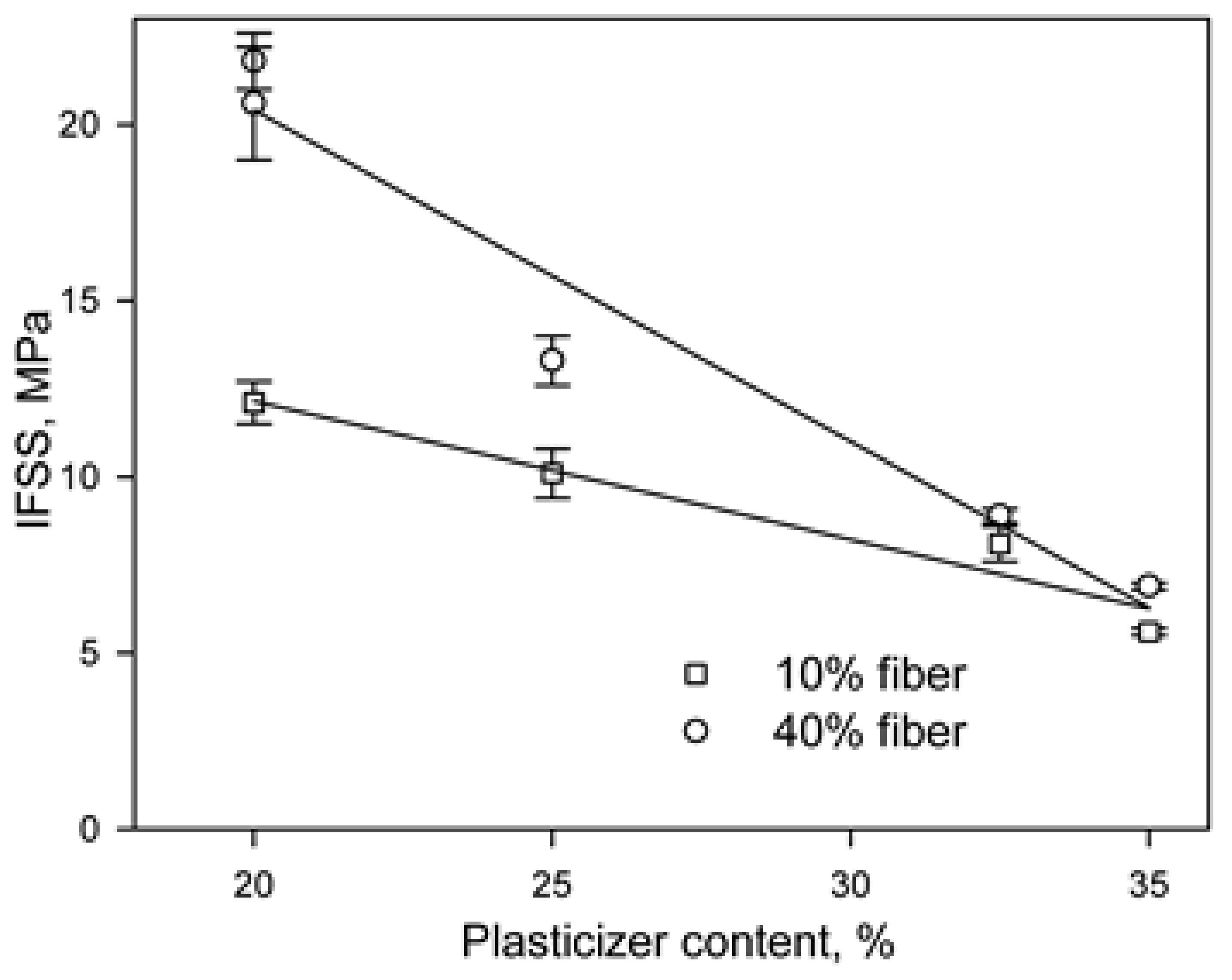
wt. %	Plast.	v_f
C37	35	10
C38	35	40

Results and Discussion

Composite (plast./fiber) wt. %	**Fiber length distribution**		η_l	η_o	**IFSS$_{ep}$, MPa**	**IFSS$_{rp}$, MPa**
	α	l_w **, mm**				
C15 (20/10)	1.5	0.39	0.69	0.43 ± 0.02	12.1 ± 0.6	11.3 ± 0.6
C16 (20/40)	1.6	0.17	0.55	0.59 ± 0.01	21.8 ± 0.8	16.1 ± 0.7
C17 (20/40)	1.7	0.17	0.59	0.58 ± 0.01	20.6 ± 1.6	16.0 ± 1.6
C20 (25/10)	1.3	0.35	0.64	0.35 ± 0.02	10.1 ± 0.7	9.6 ± 0.7
C21 (25/40)	1.4	0.28	0.69	0.40 ± 0.01	13.3 ± 0.7	12.1 ± 0.6
C28 (32.5/10)	1.4	0.37	0.46	0.48 ± 0.03	8.1 ± 0.5	7.3 ± 0.4
C29 (32.5/40)	1.3	0.32	0.58	0.41 ± 0.01	8.9 ± 0.2	8.0 ± 0.2
C37 (35/10)	1.1	0.52	0.55	0.32 ± 0.01	5.6 ± 0.1	5.4 ± 0.1
C38 (35/40)	1.3	0.32	0.52	0.41 ± 0.01	6.9 ± 0.1	6.0 ± 0.2

Elastic-plastic (IFSS$_{ep}$) and rigid-plastic (IFSS$_{rp}$) interfacial response

Results and Discussion

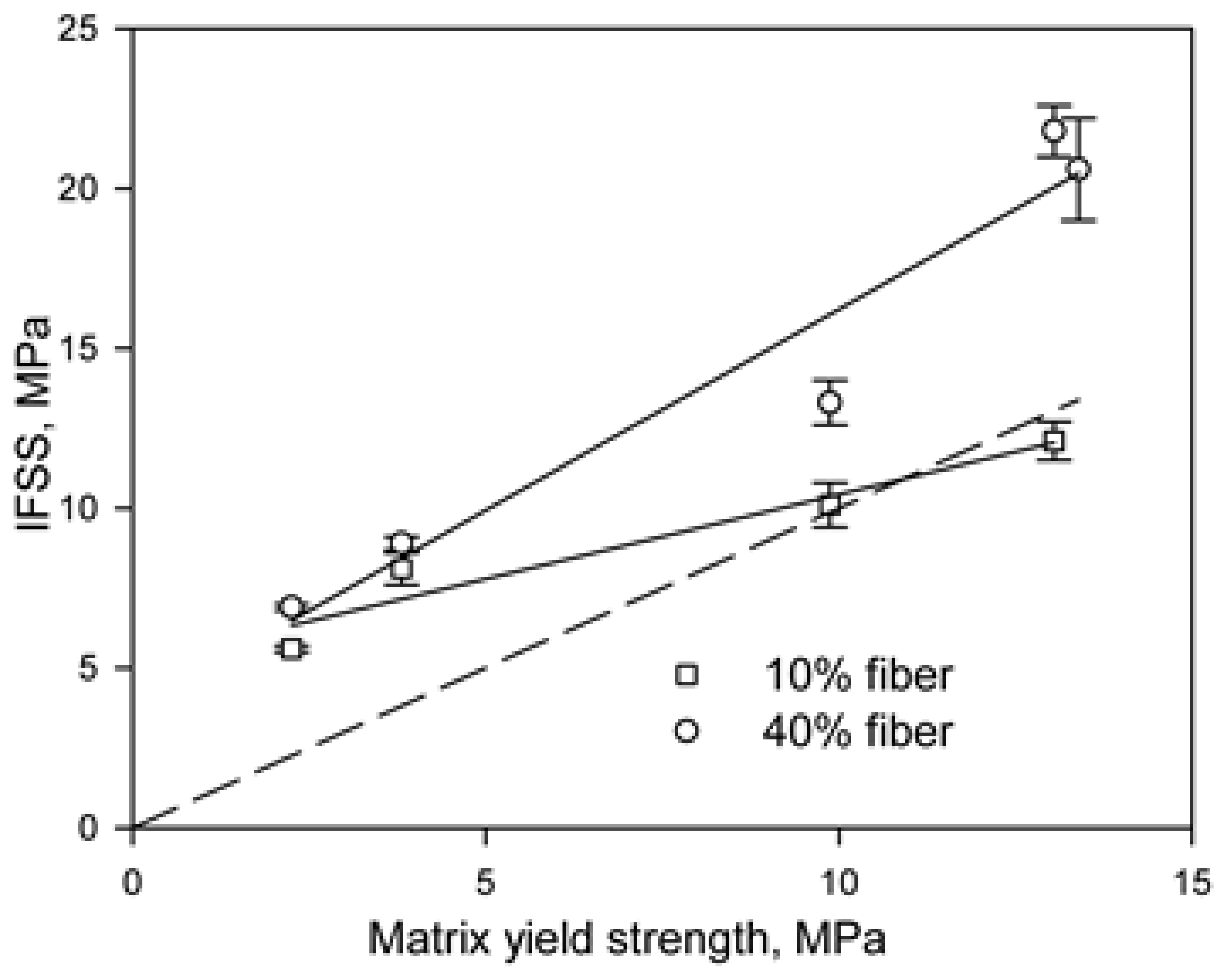


IFSS_{ep}

vs

plasticizer content

Results and Discussion

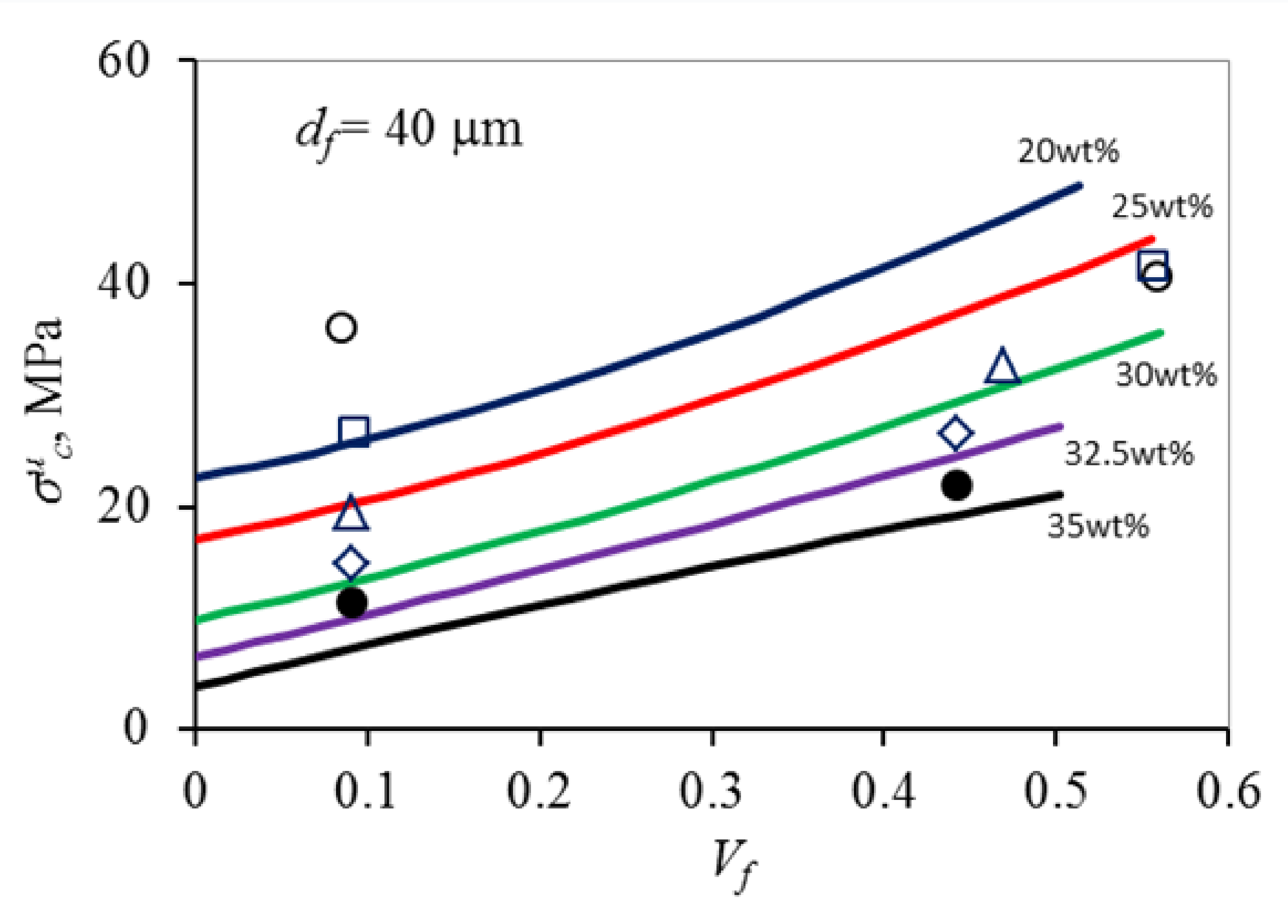


IFSS_{ep}

vs

shear yield strength of the matrix

Results and Discussion



Hemp/PSA

Summary

The Bowyer and Bader technique was modified by applying a more realistic, elastic-perfectly plastic, representation of stress transfer between fibers and matrix.

The obtained IFSS values (5 to 22 MPa) are reasonable and compare well with other similar data. The IFSS depends on fiber loading in the composites and decreases with increasing content of plasticizer in the matrix.

In general, fiber/matrix adhesion is good, as expected for chemically compatible constituents, since close correlation between IFSS and the yield strength of the matrix was observed, with the former being greater or equal to the latter.

Acknowledgement

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Thank you for your attention!