NEW TESTING EQUIPMENT FOR SHORT FIBRES

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ABSTRACT

Fibres for cement reinforcement generally are added in short-cut form of e.g. 6 mm length. To control the quality of the reinforced cement in an early stage, the tensile properties of the fibres need to be monitored. Because the testing of short-cut fibres is highly difficult, as a common practice fibre producers provide a segment of uncut tow for testing purposes. This practice bears the risk of mix-up and does not consider damage due to fibre stress during cutting. This paper introduces a new approach using a single-fibre tensile tester equipped with specially designed clamps, which open a window for precise determination of the tensile properties of even short-cut fibres. In addition, a special software algorithm allows to compensate the inherent error in elongation measurement, resulting in correct modulus and breaking elongation determination. In case of uncut long filaments the instrument can not only test the tensile properties, but also the linear density according to the well-proved vibroscopic principle. Since the linear density is related to the effective cross-section of the fibre, breaking tensions (e.g. in MPa) can be directly determined with this instrument, too. In the standard version as well as in the automated version the discussed tester it is already widely used by leading producers of PVA and PP fibres world-wide. Finally, for further tests on the uncut filament, the instrument can be equipped with wrap-bollard clamps to measure even coarse and highest-tenacity fibres, and with a special device to measure the friction along an individual fibre, which makes the instrument outstandingly suitable for tests on PVA reinforcement fibres

KEYWORDS:

Tensile testing on short-cut fibres; linear density testing on filaments.

INTRODUCTION

Tensile tests on fibres are one of the most accepted and applied tests to judge the quality and potential of PVA fibres. Usually two properties, breaking force and elongation as well as Young´s modulus, are extracted from the force/elongation-curve.

In general so-called CRE (=Constant Rate of Extension) testers (ISO 2060, ISO 5079) are used to carry out such tensile tests. A CRE tester has an ideally stationary clamp coupled to a force sensor; and a traversing clamp, which is driven with a constant speed to apply stress to the specimen.

With such a tester, as a first approximation the force can be assumed to be a function of clamp displacement, resulting in a force/elongation-diagram:

$$F = f(\varepsilon) \qquad (1)$$

With: F = Stress, e.g. in cN
ε = $\Delta l / l_0$
Δl = Increase of clamp distance
l_0 = Initial distance between clamps

The above formula (1) is based on the assumption of an ideal tester, where the test section is defined by the inner edges of the clamps holding the specimen. In real world, the most critical parts of tensile testers are those clamps. The major systematic problem is the reduction in fibre diameter due to the elongation during a tensile test, which – to a certain amount – penetrates into the zone between the clamps. As a result of this fact the fibre section of reduced diameter looses contact to the clamps and therefore also shows elongation. Since this in-clamp elongation usually is not being measured, it results in falsified elongation results. In the following we will refer to this effect as in-clamp slippage. This should not be mixed up with the slippage of the fibre through the entire clamp.

Thus, the extension measured by a tensile tester is a sum of the real sample extension and several falsifying terms:

$$\Delta l_{measured} = \Delta l_{Sample} + \Delta l_{Tester} + \Delta l_{Clamp} \qquad (2)$$

With: Δl_{Sample} = Fibre extension during tensile test
Δl_{Tester} = Tester deformation
Δl_{Clamp} = In-clamp slippage

TENSILE TESTS ON SHORT-CUT SAMPLES

The tester deformation can be neglected, since the construction of the testing instrument is extremely stiff. Furthermore the force sensor works according to the compensating principle, which eliminates any deformation of the sensor itself. Since the upper clamp is positive-locked to the force sensor and the mechanical drive of the lower clamp has nearly zero backlash, the complete measuring system has less than 0.004 mm deformation at 30 cN (a typical breaking force value for the 2 dtex PVA sample used within this study), proven by measuring the force/elongation-behaviour of a clamped razor blade.

The imperfection left is the in-clamp slippage, which only depends on the actual force. This in-clamp slippage can falsify elongation results of tensile tests dramatically, especially if the initial distance between the clamps is extremely short and the fibre sample has a high tenacity/Young´s modulus.

A common countermeasure against clamp slippage is to increase clamp pressure, which bears the risk of fibre damage. The tester has been equipped with special clamps optimised for tensile tests on short PVA fibres (clamping material, dimension and shape), which to a great extend reduce the risk of fibre damage at extremely high clamping forces, but tests have shown that still a significant slippage remains.

A suitable analysis tool to determine this slippage is to carry out tensile tests with different initial length settings of the tensile tester (e.g. according to ASTM D 3822), which has been used in the below example.

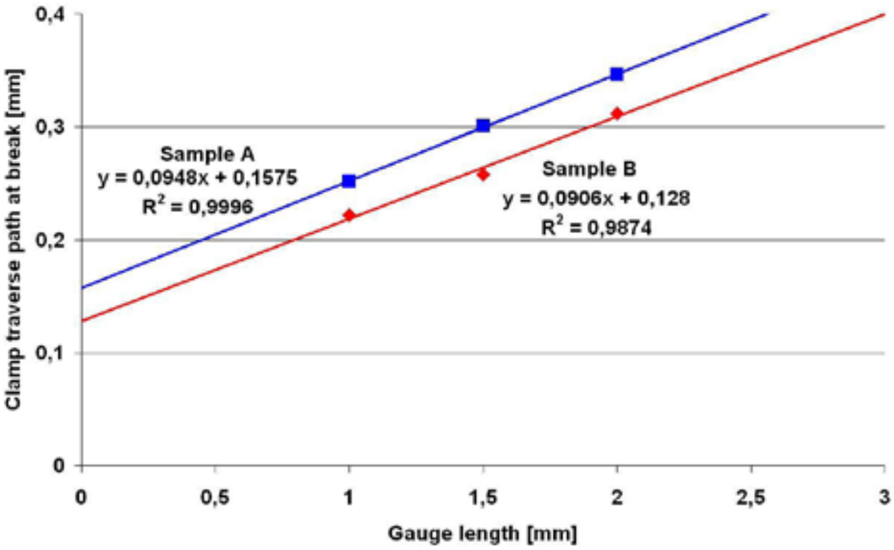


Figure 1: Elongation over initial length

Figure 1 shows the breaking elongation of two different PVA samples with initial length settings of 1 mm, 1.5 mm and 2 mm, where 25 tensile tests have been carried out on each sample. When both, the initial length and the extension, is expressed in mm, the intersection of the linear fit with the “x”-axis indicates the offset in mm to correct the initial length, the intersection with the “y”-axis indicates the clamp slippage in mm. Tests on sample “A” (lower red curve) indicate a clamp slippage of 0.128 mm, on sample “B” (upper blue curve) of 0.158 mm.

In actual common-sense practice, tests on uncut PVA samples are carried out with an initial length of 60 mm (at a test speed of 100 %/min). With an average breaking elongation of PVA of approx. 5-8% (equals to a sample extension of 3-4.8 mm with an initial length of 60 mm), the clamp slippage of approx. 0.158 mm (equals to 0.26%) respectively 0.128 mm (equals to 0.21%) can be neglected. On the other side, when using very short initial lengths like e.g. 1.5 mm, the falsifying effect becomes dramatic. The below Figure 2 and Figure 3 show the individual force/elongation-curves of 25 tensile tests of sample “A”, carried out at 1.5 mm respectively 60 mm initial length.

Tests at 60 mm initial length show an average elongation of approx. 8 %, where at 1.5 mm initial length the average elongation is approx. 20 %. Besides this remarkable error in breaking elongation, also the Young´s modulus shows a dramatic error.

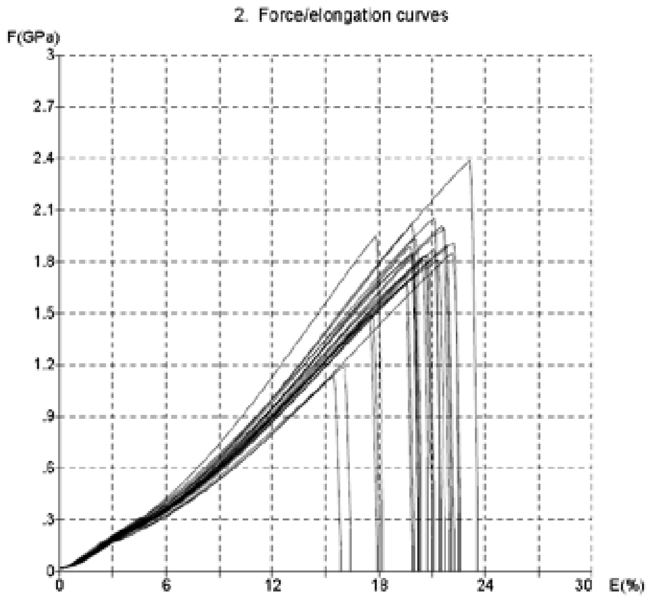


Figure 2: Uncorrected results of tensile tests on sample “A”, initial length 1.5 mm

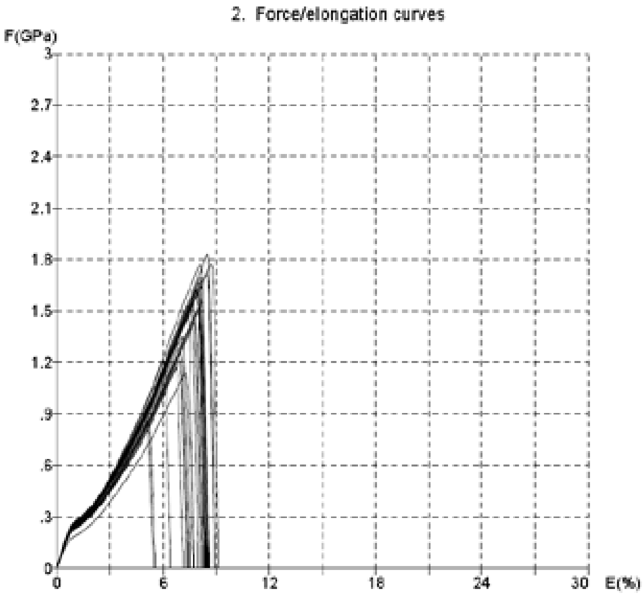


Figure 3: Tensile tests on sample “A”, initial length 60 mm

As a first measure the error in elongation can be corrected by a simple factor to compensate the in-clamp slippage, which already gives good results. However, with this simple method the force/elongation-curves do not match over the whole range. To overcome this problem, a software algorithm was developed utilizing a compensating polynomial to correct the elongation error along the whole force/elongation-curve.

To determine the coefficients of the polynomial, the a.m. tests on an uncut sample at 60 mm (as a reference) and 1.5 mm initial length are analysed. The below **Figure 4** shows the comparison of the average force/elongation-curve of both tests within one graphics.

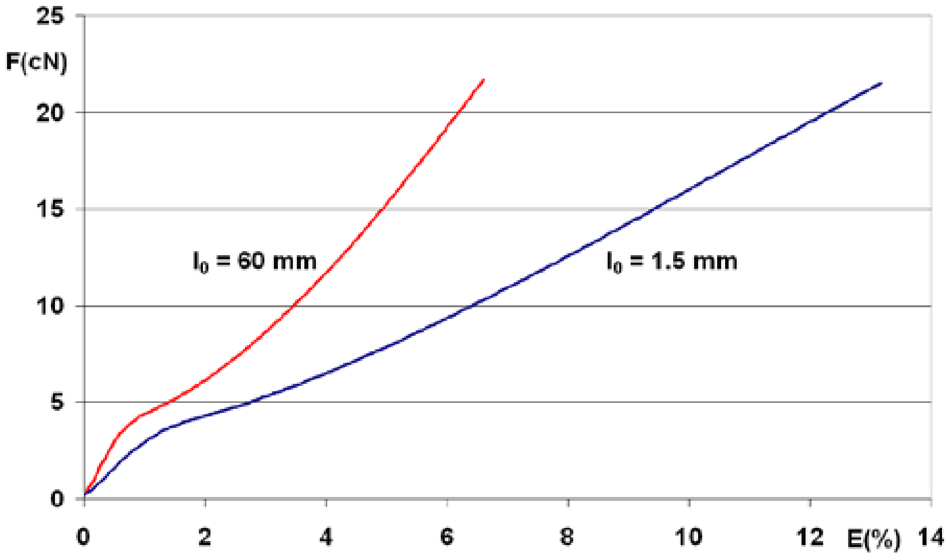


Figure 4: Comparison of average force/elongation-curves at 60 mm and 1.5 mm initial length

Finally the ratio of both elongation/force-curves is calculated and approximated by a polynomial of 5th order, which has given a satisfactory correlation. Now the elongation values of every individual force/elongation-point measured at 1.5 mm initial length are compensated by the a.m. polynomial, resulting in a force/elongation-curve which perfectly corresponds to the force/elongation-curve measured at 60 mm initial length, as illustrated in **Figure 5**. In addition to the correction by the polynomial, the illustration also includes the above mentioned compensation by a simple factor, calculated basing on the breaking elongation values of both tests.

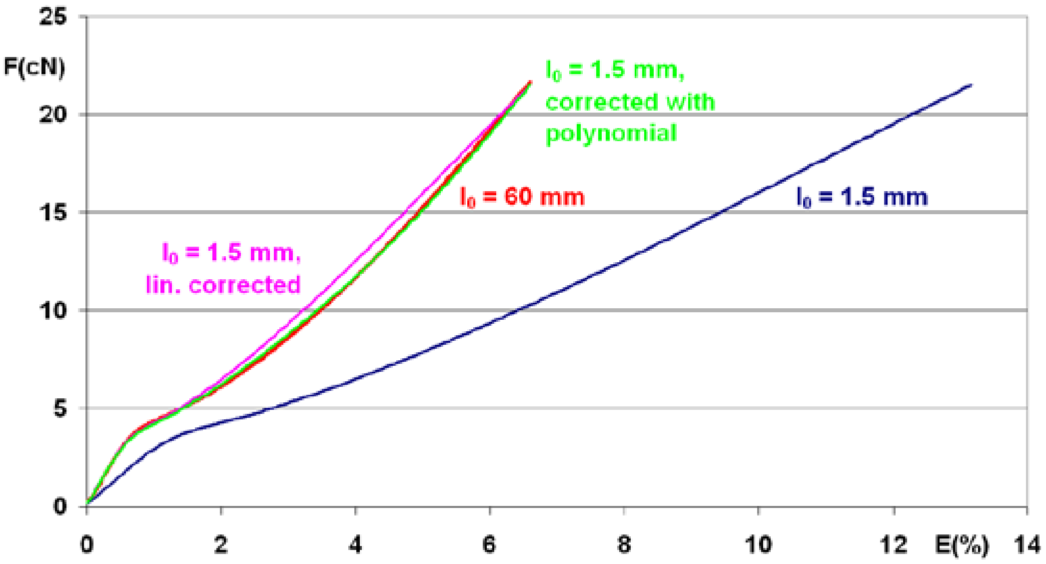


Figure 5: Original F/E-curves at 60 mm and 1.5 mm and corrected F/E-curve at 1.5 mm initial length, correction based on comparison with uncut filament measurements

With:			
	Red	=	Original curve at 60 mm IL
	Blue	=	Original curve at 1.5 mm IL
	Magenta	=	Curve compensated by factor
	Green	=	Curve compensated by polynomial

The above described method is based on a comparing study on a sample tested at 1.5 mm and 60 mm, which requires uncut filaments. In case the sample is only available as short cut fibres – e.g. if a fibre processor receives a fibre consignment without uncut filaments - a correction of the initial length according to ASTM

D 3822 (measurement at different initial length settings, refer to above) is also possible. For the sample “A” the clamp offset to correct the initial length (intersection of the linear fit with the “x”-axis, refer to Figure 1) is 1.41 mm, so that a recalculation of the force/elongation-curve results In the corrected curve shown in the below **Figure 6**. Already this measure results in a good approximation.

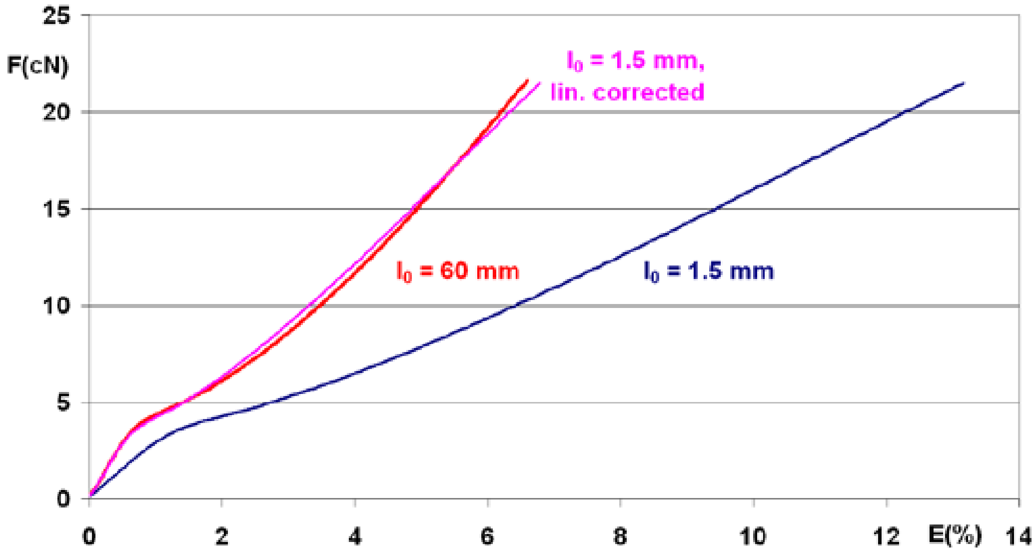
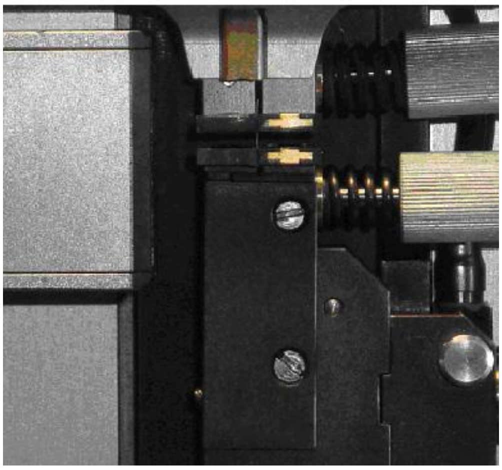


Figure 6: Original F/E-curves at 60 mm and 1.5 mm and corrected F/E-curve at 1.5 mm initial length, correction based on short-cut fibre measurements only

With: Red = Original curve at 60 mm IL
Blue = Original curve at 1.5 mm IL
Magenta = Curve compensated by factor

As a final optimisation, the tester facilitates tests on short PVA and PP technical fibres due to an optimised short fibre insertion mode, where the fibre is inserted from the top into the open lower clamp. Adjacently, after the lower clamp is closed, it travels up and thereby inserts the fibre into the open upper clamp. Last but not least the upper clamp is closed and a tensile test started.

The below Picture 1 shows the testers short fibre clamps with an inserted fibre, ready for a tensile test.



Picture 1: Short fibre clamps

LINEAR DENSITY TESTS ON UNCUT SAMPLES

On individual fibres, linear density is usually measured by the so-called vibroscopic method, where a fibre of known tension and (oscillating) length is excited by a traversal sine wave and the resonance frequency is measured. The excitation can e.g. be performed by an electric field or by acoustic sound waves, the latter principle is used in the discussed tester (**Figure 7**).

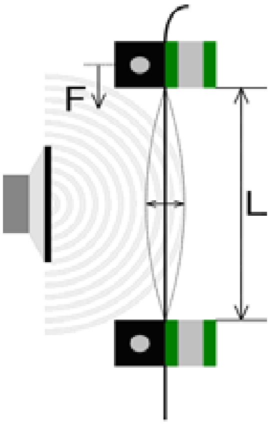


Figure 7: The principle of a vibroscopic linear-density measuring principle showing a fibre oscillating with a length L and under tension F, excited by a sound wave

The method is standardized e.g. in ISO 1973 (ISO 1973). This standard, however, names a number of restrictions as follows:

- "Useful data can be obtained on man-made fibres and, with less precision, on natural fibres."
- "Note 1: The vibroscope method may not be applicable to hollow and flat (ribbon-like) fibres."
- "Note 3: For high-modulus fibres (e.g. aramid fibres) the use of the vibroscope method should be agreed on by the interested parties, because the high stiffness of such fibres may influence the results."

These restrictions have to do with the influence of the fibre stiffness on the resonance frequency, which has been a well-known effect for many years. Based on the early findings of August Seebeck (August Seebeck, 1852) who mentioned the influence of the Young's modulus to the resonance frequency of a vibrating string, V. E. Gonsalves (1947) and D. J. Montgomery (1953) were the first to report about this effect on textile fibres/filaments. Several different, but similar alternatives of vibrating string formulae can be found in literature, allowing for different boundary conditions, as e.g. the following giving the resonance frequency f of the fundamental oscillation of a fibre (DIN 53812):

$$f = \frac{1}{2L} \cdot \sqrt{\frac{F}{T}} \cdot \left(1 + \frac{r^2 \cdot E}{L \cdot F}\right) \qquad (4)$$

with: T = linear density
F = tensioning force
L = free oscillating length
r = radius of fibre cross section
E = Young's modulus

Vibroscopic testing instruments until now don't take the second term influenced by the fibre stiffness into account, either correction factors are used in order to bring the vibroscopic results into agreement with gravimetric results (ASTM D 1577) (BISFA 1985), or the use of the vibroscopic method is mentioned to be not suitable (ISO 1973).

The formula (4) shows that the influence of fibre stiffness increases with diameter and decreases with the oscillating length and the tensioning force. This means that if only the oscillating length or the tensioning force or both are high enough, the stiffness term in the equation can be neglected as it is the case for almost all textile fibres, when testing according to the producers recommendation of vibroscopes.

In accordance with the ISO 1973 the stiffness and the cross-section shape of a fibre can be neglected if it can be proven that there is no effect to the resonance frequency.

In practice it is very easy to determine if there is an influence from fibre stiffness or not. It is sufficient to determine the linear density of a fibre under different loads at a given gauge length. If the measured linear density increases with increasing tension, there is an influence from stiffness, and either gauge length and/or tension have to be increased until there is no further increase in measured linear density. As an example the interrelation described above is illustrated for a stiff carbon fibre in **Figure 8**.

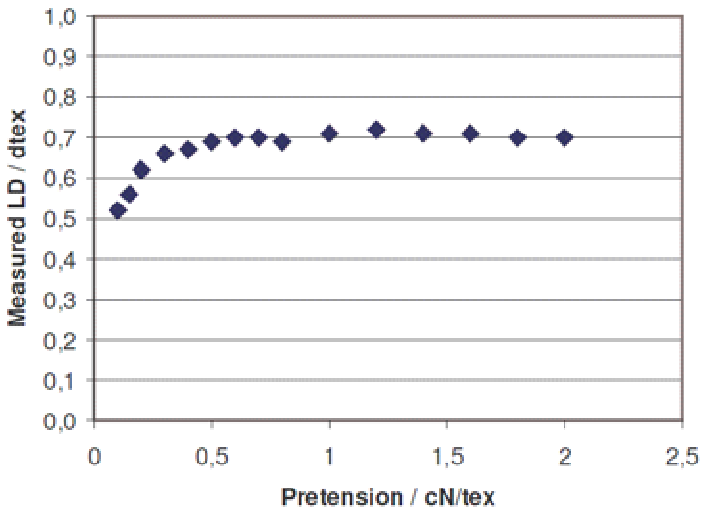


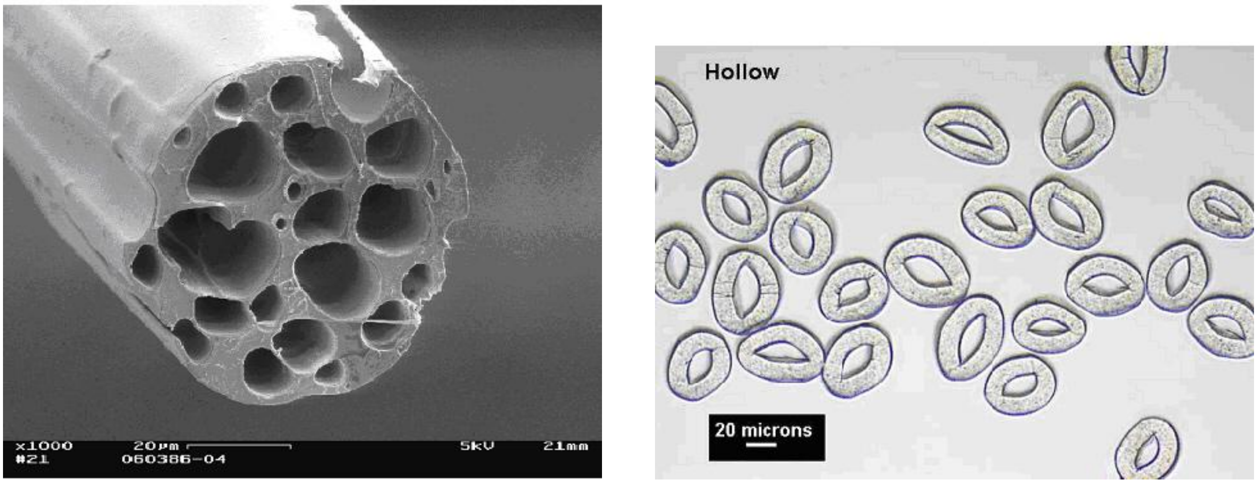
Figure 8: Influence of the applied pretension on the measured linear density of a typical Carbon Fibre

In this context the instrument has an outstanding advantage over nowadays vibroscopes because in contrast to these vibroscopes it can perform vibroscopic linear-density tests under various lengths. Hence, if at 20 mm it is not adequate to achieve a stable reading by increasing the pretension, the oscillating (gauge) length can be increased. With these means it is possible to measure the linear density of relatively stiff fibres up to 300 dtex.

The instrument also offers additional possibilities like compensation of the stiffness effect at low gauge length by means of repeated tests at several pretensions and extrapolation. Since here the clamps holding the fibre do not have to open, such tests are even possible in automatic operation. The determination of the bending modulus of fibres with isotropic cross-sections will be possible, too.

Determination of Cross-Section and Breaking Stress

Material scientists in general focus on the breaking stress, for example in N/mm² or MPa, instead of tenacity, and, therefore, need the effective cross-section area of the sample. While this cross-section is easy to determine, e.g. with a laser-scanning device for round cross-sections, it becomes more complicated for oval or tape-shaped fibres and impossible for concave cross-sections like trilobal or kidney-shaped fibres, or for hollow fibres (Picture 2).



Picture 2: Images of hollow fibres

Determination of the effective cross-section area by means of an optical or electronic microscope and picture analysis is of course possible, but very time-consuming. Here the vibroscopic linear-density test can be of help, too, since the vibroscopic method measures the fibre mass, not the diameter. Hence the following simple equation relates the effective cross-section area A to the linear density T:

$$A = \frac{T}{\rho} \qquad (5)$$

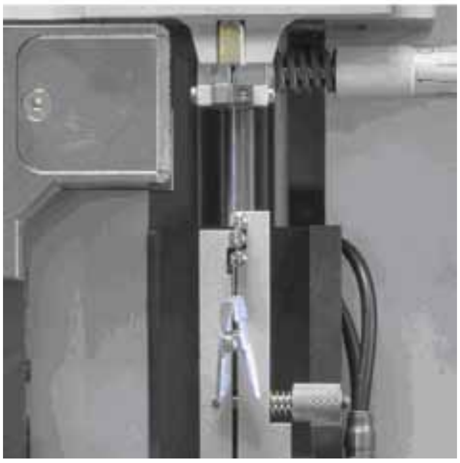
with ρ being the density of the material. The tester software allows to directly determine breaking stresses and modulus values in MPa or GPa by simply entering the sample density into the software.

FURTHER TESTS ON UNCUT SAMPLES

Especially tensile tests on extreme strong and/or thick technical fibres become very difficult due to high tensile forces, which can not be hold by a standard line clamp. With technical yarns, wrap bodies are applied to keep this high forces away from the clamps. Up to now this strategy was not applicable to individual fibre tensile testers. However. the discussed testing instrument can be equipped with a wrap-bollard clamp for individual fibres, shown in the below Picture 3. With this clamp arrangement even Ultra-High Molecular Weight Polyethylene (UHMWPE) or coarse PVA fibres (e.g. > 6 dtex) can be tested.

To complete the scope of applicable tests, individual fibre-to-metal friction can be measured, even automatically. Here, fibres are inserted with a precise pretensioning weight, and the lower clamp is replaced by a friction body. During measurement the friction body moves downward along the fibre, and the force caused by the friction is recorded as an indicator for the surface nature or spin-finish applied on the fibre. The below Picture 4 shows the a.m. friction assembly.

Picture 3: Wrap-bollard clamps for individual fibres



Picture 4: Friction assembly

The single fibre tester can be operated as a stand-alone tester for manual measurements. However, for measurements on long fibres and filaments, the tester can be equipped with a fibre storage and handling system to enable automatic testing, as illustrated in Picture 5.

Picture 5: Automatic single fibre tester system FAVIMAT (AI)ROBOT2

CONCLUSION

The above paper introduces a new and innovative testing equipment to carry out precise tensile tests even on very short fibre samples, compensating the falsifying effect of in-clamp slippage. Here two methods are mentioned, one method by comparing tensile tests results of uncut with short-cut fibre samples, and an alternative method by only analysing test results of short-fibre samples carried out at different gauge length settings. In combination with an optimised clamping system and a simple fibre insertion the instrument is well-suited for daily routine tests of short-cut fibres at both, fibre producers and fibre processors.

On uncut filaments, also linear density tests according to the vibroscopic principle are possible, here even the falsifying effect of fibre stiffness can be completely eliminated. The linear density value reported by the vibroscopic method only depends on the fibre mass, and thereby can be used to determine the tensile strength, e.g. in MPa, if the density of the sample is known.

Finally, the tester can be utilized to measure linear density and tensile properties even on coarse and extreme strong fibres and fibre-to-metal friction, the latter e.g. to determine the surface nature or evenness of spin-finish application.

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