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Influence of Fibre Length and Preparation on Mechanical Properties of Carbon Fibre/Polyamide 6 Hybrid Yarns and Composites

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Abstract
The aim of this paper was to investigate the effect of carbon fibre (CF) length and preparation prior to carding on the mechanical properties of hybrid yarns as well as composites consisting of CF and polyamide 6 (PA 6). The hybrid yarns are manufactured using an optimised process route of carding and drawing with a flyer machine from virgin staple CF (40/60/80/100 mm) and PA 6. In order to explore the effect of fibre preparation on the mechanical properties of hybrid yarns as well as composites, virgin staple CF and PA 6 fibres were prepared by varying the mixing type prior to the carding process. For this purpose, the fibres were mixed either by a fibre-opening device or supplied directly to the carding machine without prior mixing. The CF content of the card webs produced is kept at 50 volume %. Hybrid yarns were produced with a twist of 102 twist/m and then thermoplastic unidirectional (UD) composites were manufactured from them. The investigations revealed the influence of the input CF length and mixing type on the mechanical properties of hybrid yarns and thermoplastic UD composites.

Key words: *carbon staple fibre, hybrid yarn, carding, spinning, composites.*

Introduction

The concept of spinning staple carbon fibres (CF) is relatively new compared to the established spinning methods of staple fibres using conventional textile fibres. Due to the brittleness, sensitivity to shear stress and lack of natural crimp in CF, the manufacturing of slivers from staple CF as well as yarn is a challenging task compared to the processing of conventional textile fibres.

With the increased demand and usage of carbon fibre reinforced composites (CFRC), effective methods of re-using waste CF (rCF) materials, which are recoverable either from process scraps or from end-of-life components, are attracting increased attention. The ability to manufacture yarns (from staple rCF) for the production of prepreg or reinforcement structures would greatly expand the application of CFRC in vehicles and other structures where cost reduction is extremely important. To utilise the very high strength potential of CF in composites, long fibre lengths are extremely necessary. For this purpose, the gentle processing of CF for the manufacturing of yarns is decisive.

From the literature review, little information can be found so far regarding the spinning of yarns from staple CF. In patent DE 10 2009 023 529 A1 [1], a method of obtaining CF from non-crimp fabric waste and processing into yarns has been described. The process procedures of rCF spinning, particularly the carding process using a flat card, have been reported in patent US 2013/0192189 A1 [2]. However, the exact processing of yarn spinning by means of carding and further optimisation of subsequent processes cannot be found. In Patent DE 10 2010 030 773 A1 [3], the process chain of a hybrid yarn manufactured from rCF using additional coating is explained. The properties of non-crimp fabric and composites produced from wrap-spun hybrid yarns using rCF of 20 mm staple length are published in [4, 5]. However, the tensile strength of composites is found to be very low (maximum 160 MPa) and not suitable for structural applications. A method for the production of core sheath hybrid yarn from long staple CF based on ring spinning is described in [6]. The manufacturing method of producing CF spun yarn which is widely practised due to the ease of manufacturing is the stretch breaking technique, in which continuous filament tows are converted into short fibres. The most prominent manufacturers of stretch broken yarns are DuPont (Wilmington, Del.) [7], Schappe (Saint-Rembert-en-Bugey, France) [8], Pepin Assoc. (Greenville, Maine) [9], Hexcel (Dublin, Calif) [10], and Pharr Yarns (McAdenville, N.C.) [11]. Currently stretch broken CF yarns are also commercially offered by SGL [12]. However, rCF are usually supplied or available in an un-oriented form. Therefore a different approach is required in order to allign the un-oriented fibres supplied as feeding material for the processing of rCF.

The current use of CF/rCF staple fibres e.g. from production waste is mainly in nonwovens or injection molded components and is characterised by low performance. STFI Chemnitz, which has been developing nonwovens from CF/rCF for several years, has started to produce nonwoven slivers recently [13]. The strength of composites that can be achieved from the injection moulded component and from non-woven is 200-300 MPa [14] and 404 MPa [15], respectively, clearly low compared to that of 570 MPa e. g. in the case of steel (AISI 1045 hot rolled) used for structural applications [16]. Therefore from the current situation, it can be said that till now there has been no exact solution for the manufacturing of yarns which can be realized other than from stretch broken staple CF/rCF and be suitable for the manufacturing of composites to be applied in load bearing structures. Furthermore there is a lack of understanding regarding the extent of the shortening of the CF length in different process steps. The relationship of the CF length in yarn with the composite properties still needs to be explored.

In order to acquire a better understanding on the spinnablity of staple CF, extensive investigations are being carried out within the framework of a research project funded by the German Research Foundation at the Institute of Textile Machinery and High Performance Material Technology (ITM) at TU Dresden, Germany. As a result of extensive research works at the ITM, a process chain is developed for the manufacturing of a new

Table 1. *Optimum clearance between different rollers in the carding machine.*

Rollers	Clearance, mm
Worker-Cylinder	0.4
Stripper-Cylinder	0.6
Taker in-Cylinder	0.5
Cylinder- Doffer	0.8

hybrid yarn structure ensuring a gentle processing of CF [17 - 21]. A detailed description of hybrid yarn manufacturing using virgin staple CF of 40 and 60 mm and polyamide 6 (PA 6) for thermoplastic applications is reported in [21]. The hybrid yarns are produced using the process route of carding and drawing with a flyer machine.

Usually an additional preparation step is included for the processing of conventional fibres such as cotton, wool etc. prior to carding for the opening and mixing of fibres, which is crucial to improve uniformity and processability. However, till now, no fundamental investigations have been reported regarding the effect of fibre preparation on the length of CF. The aim of this study was to investigate the extent of the shortening of the CF length depending on the mixing type and input CF length, and their influence on the mechanical properties of hybrid yarns as well as on uni-directional (UD) thermoplastic composites. Investigations were carried out on the manufacturing of hybrid yarns using virgin staple CF (40/60/80/100 mm staple length) and PA 6 staple CF (60 mm length). The novelty of this research includes a comprehensive understanding of the limit of the carding process, allowing gentle processing depending on the input CF length.

Since commercially available rCF usually contains fibres of varying lengths, virgin staple CF of defined length is used to understand the extent of fibre damage occurring during different process steps for spinning. The results will help to understand the spinnability and develop yarns from staple rCF in a reproducible quality.

Experimental details

Fibre materials

For the investigations in this work, virgin continuous carbon filament tows SIGRAFIL C50 T050 EPY Carbon (SGL Carbon SE, Germany) were cut into defined lengths, such as 40, 60, 80 and 100 mm staple length (with a tolerance of ±2 mm) and used for the manufacturing of hybrid yarns. These virgin staple CFs would work as the reinforcement component in the composite.

Crimped PA 6 fibres of 60 mm length (Barnet Europe, Germany) were used as the matrix component. The reason for the selection of PA 6 is its good adhesion properties (due to available polar groups) and growing importance in automobile industries [22].

Methods

Characterizations of fibre materials

The stress-strain behaviour of individual CF and PA 6 fibre was measured with a Vibromat ME (Textechno, Germany) by following the DIN EN ISO 5079 standard. The test length was 20 mm, and a cross head speed - of 10 and 20 mm/min was used for the tensile test of CF and PA 6 fibres, respectively. Before measurement of the stress-strain behaviour, the individual fibre linear density was established by determining the resonance frequency using the same instrument following the standard of DIN EN ISO 1973. The average value was taken from 50 single fibres tested randomly.

Manufacturing of hybrid yarns

For the manufacturing of hybrid yarns consisting of virgin staple CF with PA 6 fibres, first of all carding was carried out using a laboratory long staple carding machine (Anton Gulliot, Germany) at the ITM. As damage to CF has a big impact on the tensile properties of CFRC, a long staple carding machine was used for the gentle processing of brittle CF in order to obtain higher mechanical properties in the final composites. To ensure a minimum level of fibre damage and smooth running of the carding process, an optimised clearance between different rollers was used (cf. ***Table 1***), performed by trial and error. The card clothing specifications are detailed in [21].

Two variations of card webs are produced for the investigations depending on the type of preparation of staple CF and PA 6 fibres prior to carding. The fibre preparation is carried out either by mixing the fibres by compressed air or without mixing prior to carding. The linear density and CF content of the card webs produced is approximately 30 ktex and 50 volume %, respectively.

In the case of mixing by air, the virgin CF (40/60/80/100 mm) and PA 6 are mixed gently in the quantity required using a container with compressed air at a pressure of 0.2 MPa for 10 s. After mixing, it could be observed that in the case of the 100 mm CF length, the CF and PA 6 staple fibres became strongly burled to each other compared to 40, 60 and 80 mm virgin CF. The effect of mixing in the case of the 40 and 100 mm CF length is shown as an example in ***Figure 1***.

In the other case (i.e. without prior mixing of the fibres), the fibre materials were fed directly into the carding machine without prior mixing. CFs were oriented manually in the production direction in a way that no knotting between the CF and PA 6 occured (cf. ***Figure 2*** shows an exemple for 80 mm virgin CF).

Afterwards drafting was carried out on card webs using a high performance draw frame - RSB-D40 (Rieter, Ingolstadt, Germany). The linear density of the draw frame slivers produced is approximately 3.5 ktex. Finally 800 tex hybrid yarns were manufactured from draw frame slivers on a Flyer F 15 (Rieter, Winterthur, Switzerland) at 102 twist/m. The length of different draft settings and the draft for different fibre lengths found optimum for the processing of CF on a draw frame and flyer are detailed in ***Table 2***. The slivers, hybrid yarns and unidirectional composites manufactured from the hybrid yarns and used for the investigations were identified using the code shown in ***Figure 3***.

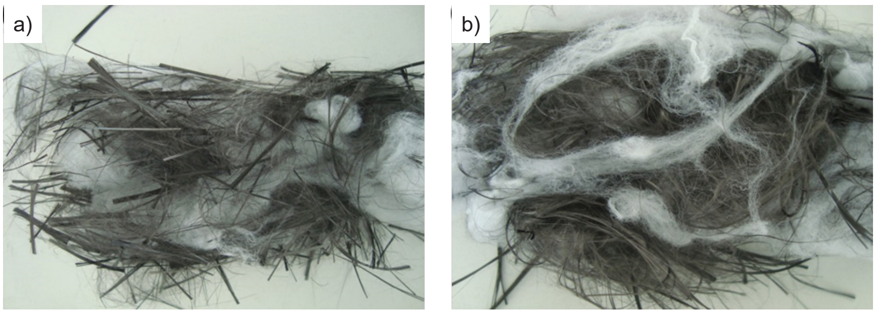

Figure 1. *CF and PA 6 after mixing in the case of a) 40 mm and b) 100 mm virgin staple CF.*

***Figure 2.** Fibre materials (80 mm virgin staple CF and PA 6) before feeding into the carding machine in the case of manually oriented virgin staple CF.*

Characterizations of fibre length distribution of virgin staple CF in hybrid yarn

In order to establish the shortening in length of CF due to different processing steps required for hybrid yarn manufacturing, the fibre length of virgin staple CF in the hybrid yarn was measured by the optical assessment method described in [23]. It should be mentioned that this optical assessment method was developed originally for determination of the greyscale value densities (GD) of pure virgin staple CF. The GD is defined as the count of pixels and their corresponding grey scale values of a defined area in the image. Each pixel has a greyscale value between 0 (pure white) and 255 (pure black). Since the proportion of GD values corresponds linearly to that of the number of fibres in a length class [23], the corresponding percentage of cumulative span length is calculated from the proportion of GD values for each length class. By plotting the percentage of the cumulative span length against each length class, the characteristic span length distribution diagram (i.e. fibrogram) and corresponding staple length diagram can be derived.

Therefore for determination of the virgin CF length in a hybrid yarn, PA 6 fibres were evaporated by thermal treatment carried out at 500°C for eight hours. Then five fibre beards were taken from the PA 6 free fibrous sample for each type using a clamp and non-sticking fibres were removed with a comb. This also parallelizes the CF at the same time. The fibre beard was glued on a white paper with a printed clamp line. The samples were scanned using an HP PSC 1410 scanner (cf. ***Figure 4***). The scanning properties are summarised in ***Table 3***.

The images were then processed with Matlab R2014a (TheMathWorks, USA) software. The GD of the individual length classes were calculated automatically. The GD values of each millimeter, starting from the clamp line, were then added in the respective length classes. Gray value 35 is defined as the border, and all values below this are specified as the background grey value and not considered. From the GD values measured, span and staple length diagrams were generated finally.

Preparation of uni-directional (UD) thermoplastic composite test specimen

In order to investigate the mechanical properties of thermoplastic composites produced from the hybrid yarns developed, UD composite plates with dimensions 274 × 274 × 1 mm were produced by the wrapping the hybrid yarn using a wrapping frame (IWT Industrielle Wickeltechnik GmbH, Germany), which was then consolidated by a Laboratory press machine P 300 PV (Dr. Collin GmbH, Germany). The consolidation was carried out by a computer-controlled cycle (under vacuum) comprisisting of a heating step from 30 to 280 °C. The temperature was kept constant at 280 °C for 1200 sec. A pressure of 0.5 MPa was applied from the beginning, reaching up to 280 °C, at which it was kept constant for 600 s. Then the pressure was increased to

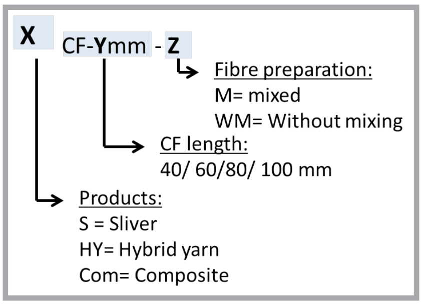

***Figure 3.** Code of identification for slivers, hybrid yarns and composites used for the investigations.*

***Table 3.** Settings of HP PSC 1410.*

Parameters	Value
Colour format	Grey-scale
File format	JPG
Resolution in dpi	300
Brightness	-72
Contrast	57

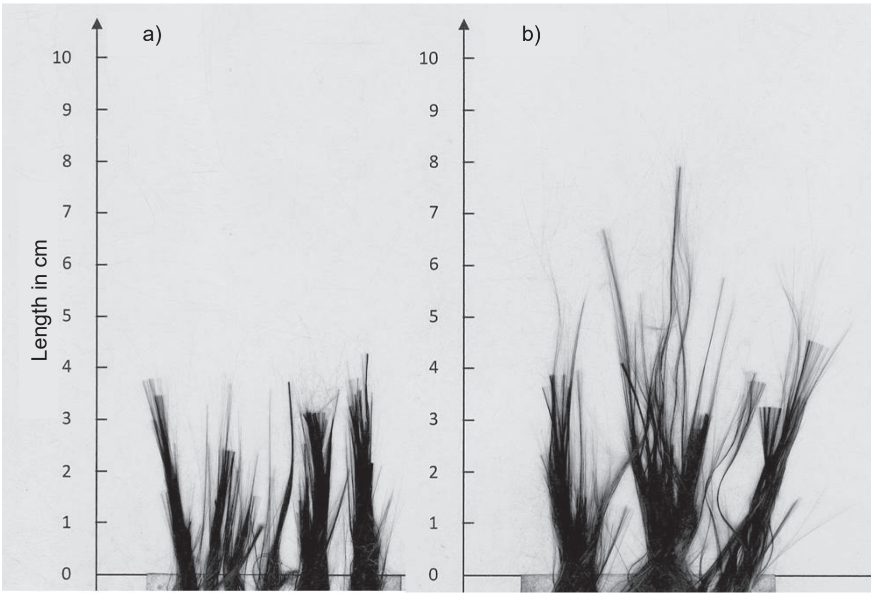

***Figure 4.** Scanned images of a fibre beard specimen prepared from PA 6 free fibrous material; a) $HY_{CF-40mm-WM}$ and b) $HY_{CF-80mm-WM}$.*

***Table 2.** Length and draft of break and main draft setting used in the draw frame and flyer.*

Drafting zone	Fibre length, mm	Draw frame		Flyer	
		Length, mm	Draft	Length, mm	Draft
Break draft	40	46	1.15	61	1.05
	60	66		71	
	80	70		71	
	100	70		71	
Main draft	40	42	5.60	50	4.78
	60	62		74	
	80	68		74	
	100	68		74	

Table 4. *Tensile properties of staple CF and PA 6 single fibre.*

Characteristics	Virgin staple CF	PA 6
Linear density, dtex	0.67 ± 0.06	4.20 ± 0.72
Tenacity, cN/tex	205.05 ± 35.05	39.93 ± 4.20
Elongation at break, %	1.64 ± 0.27	76.56 ± 7.61

Table 5. *Mean length and amount of shorter CF in hybrid yarns.*

Hybrid yarn specification	Mean CF length, mm	Amount of CF shorter than 10 mm, %
$HY_{CF\text{-}40mm\text{-}WM}$	36	13.8
$HY_{CF\text{-}40mm\text{-}M}$	34	14.4
$HY_{CF\text{-}60mm\text{-}WM}$	50	7.0
$HY_{CF\text{-}60mm\text{-}M}$	47	8.2
$HY_{CF\text{-}80mm\text{-}WM}$	65	9.5
$HY_{CF\text{-}80mm\text{-}M}$	55	11.0
$HY_{CF\text{-}100mm\text{-}WM}$	55	26.5
$HY_{CF\text{-}100mm\text{-}M}$	46	30.3

5.2 MPa and kept constant up to the end of the process. Finally the temperature was dropped down to 30 °C.

Test specimens with dimensions 250 × 15 × 1 mm were then cut out of the consolidated composite plates to carry out tensile tests in a 0° direction according to DIN EN ISO 527-5.

Test of mechanical properties of hybrid yarns

Tensile tests of the hybrid yarns manufactured were carried out according to ISO 3341 using a tensile strength testing device - Zwick type Z 2.5 (Zwick GmbH and Co., Germany) with special return clamps and external strain measurement. Samples of 250 mm yarn length were used. The test velocity was set to 100 mm/min and the initial load kept at 0.5 cN/tex. The tensile force versus deformation was recorded and 20 measurements taken to calculate the average value for each type of hybrid yarn. The stress-strain behaviour was evaluated using testXpert® software. The instrument was located in a temperature and relative humidity controlled laboratory maintained at 20 ± 2 °C and 65 ± 2%, respectively.

Test of mechanical properties of composite test specimen

The testing of the tensile properties of the UD thermoplastic composite specimen was performed on a testing device - Zwick type Z 100 (Zwick GmbH and Co., Germany) in accordance with Standard DIN EN ISO 527-5. A crosshead speed of 2 mm/min and test length of 150 mm were used for the tensile test. The elongation was measured using an optical sensor. A minimum of 10 measurements were taken to obtain the average value.

Results and discussion

Properties of fibres

The tensile properties of virgin staple CF and PA 6 fibres are detailed in ***Table 4***.

Influence of CF length and fibre preparation on the fibre length distribution of hybrid yarns

From the image analysis and GD values, the mean fibre length and amount of fibres shorter than 10 mm were calculated as detailed in ***Table 5***. It should be mentioned here that as the mechanical properties of the composites change significantly with a in the length of reinforcement fibres within a range of 1 to 10 mm [24], the amount of fibres shorter than 10 mm will have a big impact on the mechanical properties of the composites. For this reason, the amount of fibres shorter than 10 mm was calculated along with the mean fibre length of CF in the hybrid yarns.

By comparing the hybrid yarns produced from card webs prepared by mixing prior to carding with those produced without mixing, it can be seen that the mean fibre length is generally shorter and that the amount of fibres shorter than 10 mm is higher in the case of hybrid yarns produced from card webs by air mixing. These phenomena can be attributed to the higher fibre opening due to mixing prior to carding, leading to higher damage. The increase/change in the amount of fibres shorter than 10 mm present in the hybrid yarns manufactured from 40, 60 and 80 mm staple CF because of mixing before carding is comparatively lower than that in hybrid yarns produced from 100 mm staple CF. The reason is higher intermingling due to mixing in the case of 100 mm staple CF (cf. ***Figure 1***).

From the comparison between the amount of fibres shorter than 10 mm present in the hybrid yarns manufactured with different input CF lengths for both types of fibre preparation, it can be seen that the short fibre amount is the lowest in the case of 60 mm CF, which rises with an increase in the input CF length i.e. in the case of 80 and 100 mm CF compared to that in 60 mm CF. However, in the case of 100 mm input CF, the increase in the amount of shorter fibres is relatively high; the reason being the greater shortening in the CF length with an increase in the higher input CF length as a result of the bending of CF that occurs in different fibre transfer zones during the carding process e.g. between the taker in and cylinder or cylinder to doffer. Since CF is brittle and sensitive to bending, the effect of bending on fibre shortening becomes higher in the case of longer CF.

Following this argument, the amount of fibres shorter than 10 mm in the hybrid yarns produced from 40 mm CF should have been the lowest. However, the higher amount of short fibres in hybrid yarns produced from 40 mm CF compared to those produced from 60 and 80 mm input CF can be traced back to the damage that occurs during spinning on the flyer machine. Higher friction and higher damage can be observed during spinning in the case of 40 mm CF because of lower orientation, as reported in [21].

The highest mean staple length of 65 mm can be found in the case of hybrid yarn $HY_{CF\text{-}80mm\text{-}WM}$. By comparing the mean CF length and amount of shorter fibres in hybrid yarns, it can be concluded that an input CF length of 80 mm is optimum for the gentle processing of staple CF with a carding machine. The span length and corresponding staple length diagrams of the CF for the hybrid yarns are illustrated in ***Figure 5***.

Influence of fibre preparation on visual appearance of slivers and hybrid yarns

From the visual evaluation of draw frame slivers produced by air mixing (cf. ***Figure 6***), it can be seen that the intermixing between virgin staple CF and PA 6 staple fibres is relatively better as a result of higher individualization of virgin staple CF. On the other hand, in draw frame slivers produced from card webs without mixing prior to carding (i.e. by feeding and orienting the virgin CFs manually), bundles of virgin staple CF (i.e.

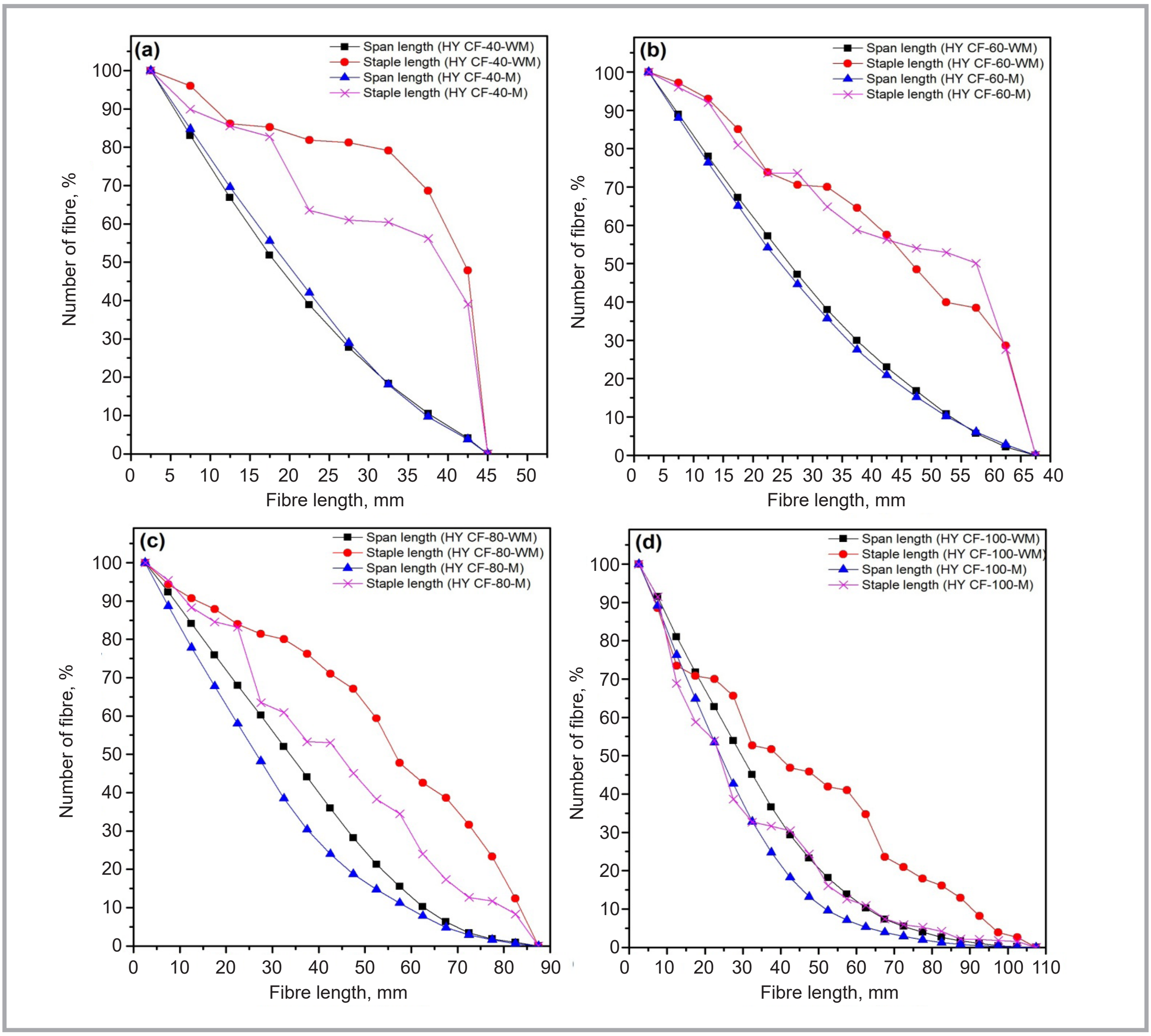

Figure 5. *Span length diagram of virgin staple CF in hybrid yarns in the case of a) 40, b) 60, c) 80 and d) 100 mm CF depending on the type of fibre preparation.*

unopened) can be easily recognised. As a results, the slivers produced from card webs prepared by mixing with air seem visually more homogenous.

The same tendency can be observed in the visual appearance of the hybrid yarns, as illustrated exemplarily in ***Figure 7*** in the case of $HY_{CF\text{-}80mm}$ produced from card webs prepared by air mixing and without mixing.

Influence of CF length and fibre preparation on the mechanical properties of hybrid yarns

From the results for the tenacity of hybrid yarns depending on the CF length and fibre preparation illustrated in ***Figure 8***, it can be seen that the fibre length has an influence on the hybrid yarn tenacity. In the case of hybrid yarns for both types of fibre preparation, a tendency can be seen that the tensile strength of hybrid yarns increases with an increase in the input CF length from 40 to 80 mm. The tensile strength of hybrid yarns decreases in the case of 100 mm input CF. The hybrid yarns produced with

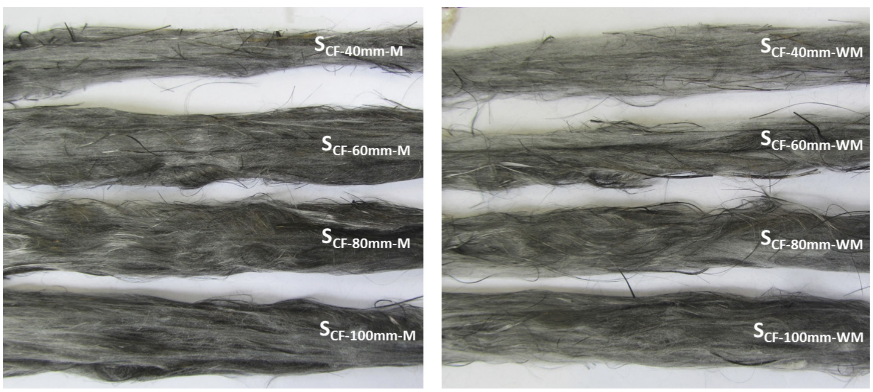

Figure 6. *Influence of fibre preparation and input virgin CF length on the visual appearance of draw frame slivers.*

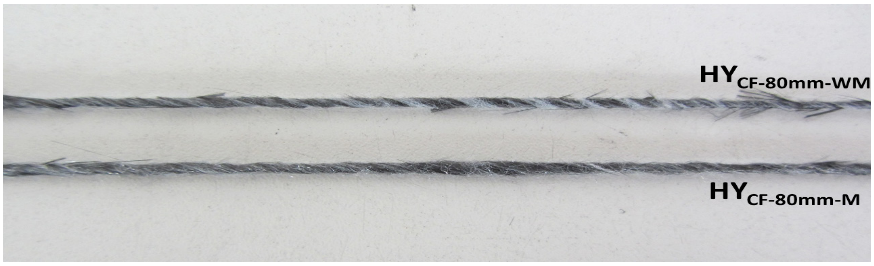

Figure 7. *Hybrid yarns $HY_{CF-80mm}$ with/without mixing.*

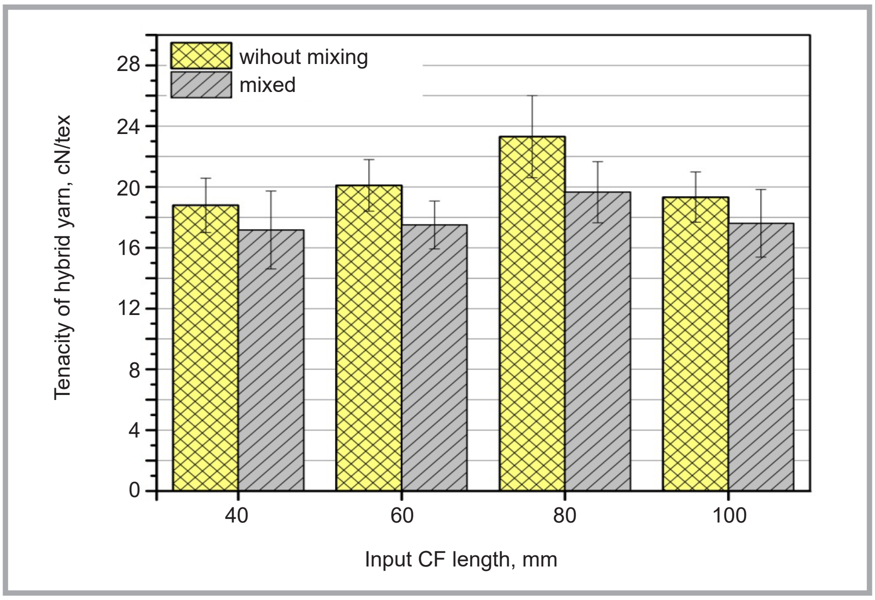

Figure 8. *Tenacity of hybrid yarns depending on input CF length and fibre preparation.*

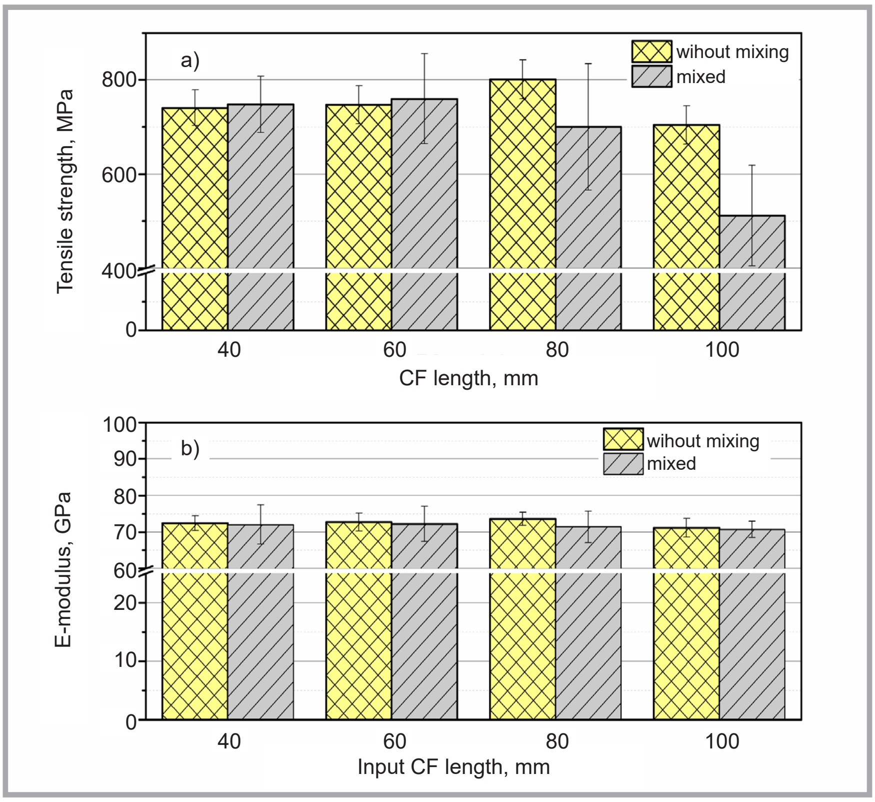

Figure 9. *Average tensile strength (a) and E-module (b) of UD thermoplastic composites made from hybrid yarns in dependence on different lengths of the CF and fibre preparation.*

an 80 mm fibre length possess the highest strength for both variants i.e. the hybrid yarns produced from card webs with and without mixing. Moreover it can be seen that the hybrid yarns produced from card webs without mixing exhibit higher strength than those produced with mixing for all the input CF lengths. This is clearly the effect of the mean CF length and the amount of short fibres present in the hybrid yarns (cf. ***Table 5***).

Influence of CF length and fibre preparation on the tensile strength and E-module of UD thermoplastic composites

The results of tensile strength and E-module tests of UD thermoplastic composites with 50 volume % CF content produced from virgin staple CF by varying the CF length and fibre preparation are illustrated graphically in ***Figure 9.a*** and ***9.b***, respectively. By comparing the tensile strength of UD composites for all four input CF lengths, a weak tendency could be observed where the tensile strength increases slightly with an increase in the input CF length up to 80 mm, and then decreases for 100 mm CF.

From the comparison of the tensile strength of UD composites manufactured with the same CF length and varying the fibre preparation, no difference in tensile strength can be found in the cases of 40 and 60 mm CF used as the starting material. It seems that the better mixing as a result of mixing prior to carding contributes to increasing the strength of the composite; however, the mean CF length in the hybrid yarns is slightly lower compared to those manufactured without mixing. However, the effect of fibre preparation is prominent in the case of 80 and 100 mm CF. The tensile strength decreases significantly due to air mixing as a consequence of greater shortening of CF and a higher amount of shorter CF in the case of 80 and 100 mm CF.

The results of E-module tests (cf. ***Figure 9.b***) show the same tendency as found in the case of tensile strength tests. Stress-strain diagrams of $Com_{CF-80mm-WM}$ are shown exemplarily in ***Figure 10***. Results of the tensile tests of UD composites are summarised in ***Table 6***.

The results of the tensile tests in our research show that the hybrid yarns developed have a maximum tensile strength and E-module of 801 ± 41.6 MPa and 74.4 ± 1 GPa, respectively (cf. ***Table 6***).

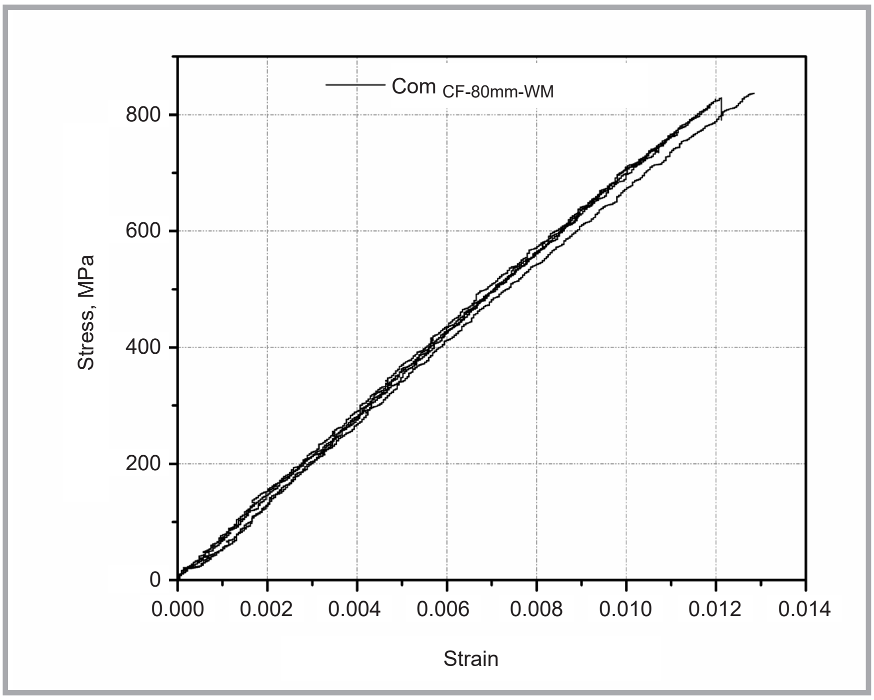

Figure 10. *Stress strain diagrams of composites in the case of Com $_{CF-80mm-WM}$.*

Table 6. *Tensile strength, E-module and elongation at break of UD composites produced from hybrid yarns using different lengths and fibre preparation.*

Identification of composite specimen	Tensile strength, MPa	E-module, GPa	Elongation at break, %
$Com_{CF-40mm-WM}$	741.0 ± 37.8	72.4 ± 2.0	1.0 ± 0.1
$Com_{CF-40mm-M}$	748.6 ± 59.3	72.0 ± 5.4	1.1 ± 0.1
$Com_{CF-60mm-WM}$	747.0 ± 40.5	72.7 ± 2.4	1.1 ± 0.1
$Com_{CF-60mm-M}$	760.0 ± 95.9	72.2 ± 4.8	1.0 ± 0.1
$Com_{CF-80mm-WM}$	801.0 ± 41.6	73.6 ± 1.8	1.2 ± 0.1
$Com_{CF-80mm-M}$	700.0 ± 134.4	71.4 ± 4.3	0.9 ± 0.2
$Com_{CF-100mm-WM}$	704.0 ± 40.9	71.1 ± 2.6	1.0 ± 0.1
$Com_{CF-100mm-M}$	512.0 ± 107.0	70.7 ± 2.3	0.8 ± 0.2

Therefore by comparing the tensile properties of conventional materials used as the structural component (as already mentioned in the introduction part), the hybrid yarns developed through the optimization of different processes have very good potential for structural applications. This would greatly expand the application of CFRC in vehicles and other structures, where cost reduction is extremely important.

Conclusion

The investigations show that the input CF length and mixing prior to carding have a big influence on the tensile properties of hybrid yarns. Due to mixing before carding, the mean staple length decreases and the amount of CF shorter than 10 mm increases. As a result, the ensile strength of hybrid yarns produced by mixing is found lower than those produced without mixing. By comparing the influence of the CF length on the hybrid yarn strength, it can be seen that the tensile strength of hybrid yarns increases with an increase ini the input CF length from 40 to 80 mm. By comparing the tensile strength of composites manufactured with the same CF length and varying the fibre preparation, it can be revealed that the effect of the fibre preparation is not significant in the cases of 40 and 60 mm CF. However, in the case of 80 and 100 mm CF, the tensile strength is found lower in the case of fibre mixing prior to carding. The results of tensile tests of UD composites show that there is a weak tendency towards an increase in the tensile strength with an increase in the input CF length from 40 to 80 mm. The tensile strength of composites manufactured from 100 mm CF is found to be the lowest because of the presence of a higher amount of shorter CF. The findings of the investigations show the current limit of the input CF length which can be processed gently by means of carding, drawing and spinning since the fibre length distribution of rCF is very broad and usually contains fibres longer than 100 mm. Therefore in order to utilise the full potential of CFRC manufactured from rCF, there is a requirement for further research of the gentle processing of CF longer than 100 mm.

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