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Comparing the packing densities of yarns spun by ring, compact and vortex spinning systems using image analysis method

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This study is aimed at determining the packing densities of yarns produced by different spinning systems to investigate the fibre distributions for each system. For this purpose, 100% Tencel LF yarns with 19.69 tex linear densities are produced on ring, compact and vortex spinning systems. Cross-sections have been made by hard sectioning method using a rotary microtome. Packing densities of yarns are calculated by image analysis method. Results show that the compact yarns have the highest packing densities while vortex yarns have the lowest. However, differences between the packing densities of ring and compact yarns are not found statistically significant. In this study, density values of yarns (D, g/cm^3) are also measured by Uster Tester 5 to evaluate the relationship between the packing density and yarn density values. Results show that the packing density values are parallel to yarn density values.

Keywords: Compact-spun yarn, Image analysis, Packing density, Ring-spun yarn, Tencel LF, Vortex spun yarn

1 Introduction

Yarn physical, structural and mechanical properties or in other words yarn quality are highly affected by fibre properties such as type of raw material, fibre length, fibre fineness, fibre strength, etc. In addition to these fibre properties, fibre arrangement in yarn structure also affects yarn behavior. Packing density expresses degree of arrangements of fibres in yarn structure and it is calculated by the ratio of total area of the fibres to the cross-sectional area of the yarn. Yarn diameter, yarn compactness, yarn contraction, yarn porosity and yarn volume are directly affected by packing density of yarn. Moreover, spinning technology has important role in affecting yarn properties or quality and it also affects fibre arrangement in yarn structure. This study is aimed at investigating the packing densities of 100% Tencel LF yarns produced by different spinning systems (ring, compact and vortex) to provide a better understanding of the effect of spinning system on internal structure of yarns.

In packing density evaluation, there are various approaches used by different researchers. The first one was proposed by Schwarz[1] in 1951 and developed by Balakrishna Iyer and Phatarford[2] in 1965. In this approach, the number of filaments in a yarn cross-section was very small, ranging from 1 to 37. Their assumption was that the fibres in the yarn cross-section arranged into close hexagonal configurations. But, this method was not suitable to be applied to staple yarns. The second approach was based on the assumption that there was a circular arrangement of fibres in yarn cross-sections[3, 4]. In this case, the yarn cross-section was divided into several circular zones of equal widths or equal areas. In 1959, Hamilton[5] suggested a direct method of measuring yarn diameters and bulk densities under conditions of thread flattening. Later on, Hearle *et al.*[6] gave some formula to calculate specific volume of yarn based on yarn twist, twist angle and yarn linear density. The formula given by Hearle *et al.*[6] was only valid in the case of an idealized ring yarn structure, and was not applicable for other spinning systems. In this regard, Ishtiaque and Khare[7] derived a formula to calculate the packing densities of the yarns produced by different spinning technologies. Doğu[8] indicated fibre packing density as a function of the radial distance and defined it as the number of fibres per unit area perpendicular to fibre axis. Driscoll and Postle[9] defined fibre distribution as the ratio of fibre volume to yarn volume at radius (r). Neckar *et al.*[10] and Punj *et al.*[11] also used similar approaches by dividing yarn cross-section into several circular zones having equal widths or equal areas.

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While going through the literature it has been found that many researchers have dealt with the inner structures of yarns spun by different spinning systems. Ishtiaque and Khare[7], investigated the internal structure of ring, rotor and air-jet spun blended yarns by cross-sectional view. Results showed that the packing density of rotor yarn is less than that of the ring yarn. Also, the higher rotor yarn diameter is responsible for the low packing density. However, yarns spun from air-jet system consists of bundle of parallel fibres wound by some tight wrapper fibres. Jiang *et al.*[12] studied on cross-sectional packing density of rotor-spun yarns. In this study, a detailed method for determining the packing density is described. In addition, a study on the relationship between packing density and yarn parameters such as yarn count and twist factor is included. Kumar *et al.*[13] have investigated the effects of spinning process variables such as the lap hank, card draft, draft/doublings and drafts on the packing density of ring, rotor and air-jet yarns using the Taguchi method. Results showed that the yarn diameter was the highest and the packing density was the lowest for rotor yarns. On the other hand, the yarn diameter was the lowest and the packing density was the highest in air-jet yarns. Packing density was inversely related to the diameters of ring, rotor and air-jet yarns. The packing density of ring yarns tends to increase with the decrease in helix angle, and the packing density of air-jet yarns tends to increase with the increase in helix twist. The change in card draft influences most of the change in helix angle, helix twist, yarn diameter and packing density. Yılmaz *et al.*[14] have studied the fibre distribution through the cross-sections of compact yarns and their packing density values to provide a better understanding of the internal structures of compact yarns produced by different compact spinning systems. Packing density analysis results showed that packing densities of all compact yarns were not uniform in yarn cross-section, but decreased from yarn center towards the yarn surface, as it was the case for conventional ring spun yarns too. On the other hand, there was no significant difference between the packing density values of the yarns produced on the three different compact spinning systems. They concluded that compact yarns have almost 30% higher packing density compared to that of conventional ring spun yarns and such a compact structure would of course affect yarn properties significantly. Ishtiaque *et al.*[15] worked on the influence of process parameters on packing density of open-end and core-sheath friction spun yarns. The effect of opening roller speed, difference in drum speed and suction air pressure on packing density parameters of open-end and core-sheath friction spun yarns have been analyzed using the Box-Behnken method and response surface equations. They have concluded that core-sheath friction yarns have lower yarn diameter and helix angle, but higher packing density than open-end friction yarns. Zheng *et al.*[16] analyzed the fibre distribution pattern in yarn cross-section for vortex-spun yarns by using image processing method based on Photoshop software. They aimed to provide a better understanding of the internal structure of vortex-spun yarns by focusing on the fibre distribution pattern in its cross-section. Fibre packing density results indicated that the fibre packing density values from yarn axis to yarn surface were not uniform in yarn cross-section. Compared to conventional ring-spun yarns, the fibre packing density of vortex-spun yarns was lower at the yarn center and surface, but fibre effective packing density in yarn cross-section was higher, showing that different spinning methods have different fibre packing densities. Results also showed that the fibre packing density and the fibre effective packing density for vortex-spun coarser yarns were higher than that of finer yarns.

This study was aimed at analyzing the effects of spinning systems on fibre distributions and packing densities that affect most of the yarn properties. For this purpose, yarns produced by ring, compact and vortex spinning systems were used.

2 Materials and Methods

In this study, 100% Tencel LF yarns were produced systematically in ring, compact and vortex spinning systems. As it is known, tencel is a regenerated cellulosic fibre which has unique nanofibril structure. It absorbs excess liquid and quickly releases it again into the atmosphere, and so it provides natural hygiene. Tencel makes the skin feel soft and pleasant. For these reasons, Tencel LF has a wide range of use in practice from home textiles to underwear, sportswear, work wear and denim. Besides the common use in practice, Tencel LF fibres have circular cross-section and hence were especially selected for this study to eliminate the influence of irregular cross-sectional shape and to analyze the effect of spinning systems on packing density more accurately. Some properties of Tencel LF fibres are given in Table 1.

In this study, Tencel LF yarns with linear density of 19.69 tex were produced separately on ring, compact and vortex spinning systems to investigate the effect of spinning system on packing density. Twist multiplier was selected as α_e = 3.7 for ring and compact yarns. The corresponding twist level was set for vortex yarns by considering the production parameters specified in Murata's machine catalogue.

All the slivers used in the study were produced on a Trutschler DX 760 blowroom and carding machine. A Vouk SHL drawframe was used in the drawing processes. Six doublings and six drafts were applied in all drawing passages and Ne 0.130 slivers were produced. Two passages of drawings were applied to 100% Tencel LF slivers. A Zinser 668 roving frame was used in the production of ring and compact yarns and Ne 1.03 rovings were produced. Ring yarns were spun on a Suessen Fiomax 1000 ring spinning machine and compact yarns were spun on a Suessen Fiomax E1 compact spinning machine. Finally, vortex yarns were spun on a Murata Vortex Spinning (MVS) 861 vortex spinning machine[17].

2.1 Sectioning

Preparation of the yarn cross-sectional samples is significant for investigation of packing density of yarns. There are two methods to obtain yarn cross-sectional samples, namely soft sectioning and hard sectioning. In this study, hard sectioning method was used. In this method, each of the yarn samples was placed into polyvinyl chloride (PVC) tube sealed at one end. Yarn axis must be parallel to PVC tube axis. Preparation of embedding medium consisted of two steps. First step included the preparation of infiltration solution by mixing 50 mL 2-hydroxyethyl-methacrylate as basic resin/liquid and 0.5g dibenzoyl peroxide as activator in a magnetic stirrer until dissolved completely. Second step included the preparation of embedding medium by adding 1 mL dimethyl sulfoxide as hardener per 15 mL infiltration solution. The yarn samples were kept ready to sectioning after waiting for about 18-24h at room temperature for polymerization of embedding medium. After these procedures, yarn cross-sectional samples were sliced by Leica Rotary Microtome (RM2125RT). The thickness of samples was taken as 3 μm.

Table 1—Properties of Tencel LF fibres

Property	Value
Titer, dtex	1.3
Cut length, mm	38
Tenacity, cN/tex	37
Elongation, %	13
Tenacity in wet state, cN/tex	30
Elongation in wet state, %	15

2.2 Calculating Packing Density with Image Analysis Method

In recent years, image analysis method is used to find conjectural data about textile products. Identification of fabric defects, prediction of pore properties of yarn and fabrics, calculation of yarn packing density, and prediction of yarn diameter and irregularity are some examples of these researches[14, 18].

An image can be defined as a two-dimensional function as $f(x,y)$, here x and y coordinates of the function determine the intensity or gray level of the image at that point[19]. Digital images consist of a finite number of elements called pixels. Image processing is a signal processing method in which the input of the system is an image and output is an image or the property of this image. Image analysis processes are used in order to define the object better. The first step of image analysis is capturing the image. After having digital image, some pre-processing steps are applied to improve it[20]. Images may be in the form of true color image, gray-level image or binary images. In color image every pixel is defined with three values which are red (R), green (G) and blue (B). Grayscale images consist of 256 grey tones. Zero grey level value denotes black and 255 grey level value denotes white color in the gray scale. Binary image in which a pixel is 0 or 1 is obtained after segmentation of the image. This is the most important and difficult step in image analysis because there can be some error deciding the pixel value. It is aimed to determine most suitable threshold value (T) when converting grey level image to the binary image. The pixels of grey level image are classified as white or black color, depending on threshold value according to the equation as given below[21]:

$$g(x,y)=\begin{cases}1 & f(x,y)\geq T\\ 0 & f(x,y)<T\end{cases} \quad \ldots (1)$$

In general, there are two methods for determination of packing density, namely direct method and secant method. In this work, packing densities of yarns were determined by direct method. Direct method is based on the detection of real fibre area. Real fibre images have to be pretreated before evaluation. The separation of individual images, transformation to binary form and noise removal are also necessary[22].

In this study, the cross-sectional images of the yarns were captured in order to examine the packing densities of the yarns produced by different spinning systems using image analysis method. After sectioning processes, the digital cross-sectional images of yarns were obtained by using a camera integrated to a research microscope (Olympus BX43), as shown in Fig. 1(a). A ×20 magnifying lens was used to produce 8-bit grey level image having the size of 2080x1544 pixel to analyze the structure of the yarn in detail. The images were improved and analysed by a computer system and necessary softwares (Photoshop, Matlab) having image processing instruments.

In the second step, obtained cross-sectional images of yarns were pre-processed using Photoshop program. The images were cropped and the background of the images were eliminated by using Photoshop toolboxes [Fig. 1(b)]. Then, the grey level image was converted into binary image in the image analysis program using the Matlab image processing toolbox [Fig. 1(c)]. The purpose of this process was to identify the fibre and pore areas in the yarn cross-section by using a suitable threshold value. The value of the pixels higher than the defined threshold value was converted into white pixels and lower ones were converted into black pixels. In this study, the Otsu method was used. This is a histogram based global thresholding method. In this method, first the histogram of the image was obtained and then the variances of the images were calculated for each threshold value. The value which maximizes the between-class variance was chosen as threshold value[21]. In binary image, black pixels represent fibres, and white pixels represent pore areas. This final binary image was used to calculate the packing density of the yarn. The last step is to predict the cross-sectional area of the yarn. For this purpose, the cross-sectional shape of the yarn was assumed being ellipse. The image size ($M \times N$) of the final binary image was supposed equal to ellipse size and it was used in calculation of total yarn area [total yarn area = $\frac{\pi MN}{4}$]. In Fig. 1(c), the red line simulated the boundary of the yarn. In this step, the fibres located out of the predicted yarn boundary was ignored. Finally, the packing density was calculated using the ratio of the total black pixels represented total fibre area to the total yarn area. In Fig. 1, steps of image analysis method and the predicted yarn area are summarized.

2.3 Measuring Yarn Density and Diameter

In this study, in addition to fibre packing density, density (D, g/cm^3) and diameter (2DØ, mm) values of yarns, which are thought to be related to fibre packing density, were also measured by Uster Tester 5 S800. The test was performed at 400 m/min test speed throughout 2.5 min. Density and diameter values of yarns are absolute measures for yarn's compactness. Density value of yarn is calculated as follows:

$$m = \frac{d^2\pi}{4}\ l\ D\ (g) \qquad \ldots (2)$$

$$D = \frac{4m}{d^2\pi\ l} = \frac{4}{d^2\pi}.\frac{m}{l}\ \ (g\ /\ cm^3) \qquad \ldots (3)$$

$$\frac{m}{l} = \text{ Yarn count } (g\ /\ cm) \qquad \ldots (4)$$

where m is the mass of yarn; l, the yarn length; d, the yarn diameter in cm; and D, the yarn density in g/cm^3 (ref. 23).

3 Results and Discussion

In this study, 100% Tencel LF ring, compact and vortex yarns have been investigated to better understand effects of spinning systems on fibre

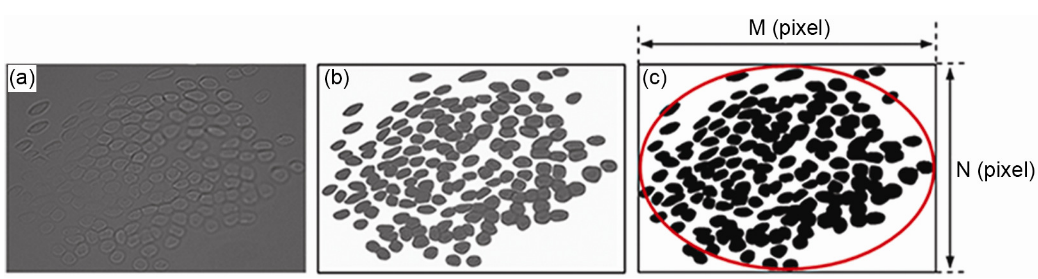

Fig. 1—Image analysis steps (a) raw image, (b) image after Photoshop processes and (c) image after image processing

distributions and packing densities that affect most of the yarn properties. Tencel LF fibres having circular cross-sections are especially selected to eliminate the influence of irregular cross-sectional shape and to analyze only the influence of spinning systems on packing density. Packing densities of ring, compact and vortex yarns are shown in Table 2. It is observed that the compact yarns have the highest packing density while vortex yarns have the lowest. Compact spinning system eliminates spinning triangle with air guide element mounted on the perforated drum. Individual fibres are straightened and arranged parallel with one another by means of aerodynamic forces. Most fibres in the compact yarns are integrated into yarn body[24, 25]. On the other hand, vortex yarns are known as fibre bundles with wrapper fibres wrapped on parallel fibre core[26, 27]. Figure 2 shows longitudinal SEM images of ring, compact and vortex yarns used in the study. It is clearly seen that compact yarn has the most even and close structure. Moreover, ring has hairy structure in comparison with compact yarn and lastly vortex yarn has the specific wrapper structure. In this study, parallel results have been found after cross-sectional analysis of the yarns. Figure 3 shows the cross-sectional images of ring, compact and vortex yarns.

Table 2—Density, diameter and packing densities of ring, compact and vortex yarns

Spinning system	Density (*D*) g/cm^3	Diameter (2*D*Ø) mm	Packing density %
Ring	0.66	0.194	38.01
Compact	0.67	0.194	41.91
Vortex	0.58	0.208	23.86

The analysis of variance (ANOVA) has also been performed to determine the effect of spinning system on yarn packing density statistically. Results show that the effect of spinning system on yarn packing density is statistically significant for α=0.05 significance level [Table 3 and Fig. 4(a)].

Although the mean values of packing density of compact yarns are higher than the ring yarns (~10%), pairwise comparison [Fig. 4(a) and Table 4] shows that differences between ring and compact yarns are not statistically significant for packing density values. This result may be the main factor for many

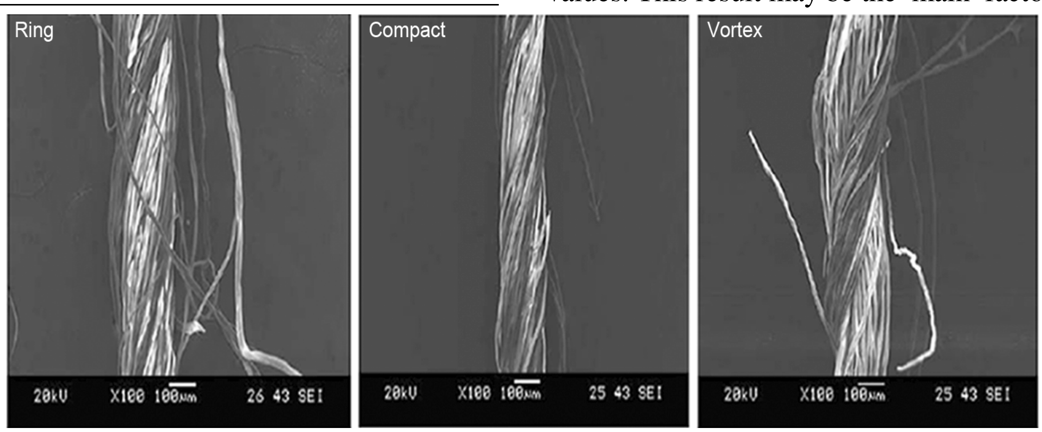

Fig. 2—SEM images of ring, compact and vortex yarns

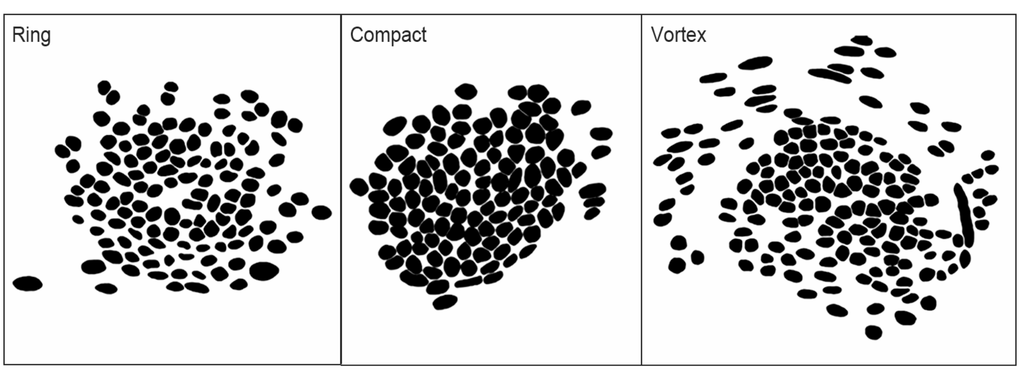

Fig. 3—Cross-sectional images of ring, compact and vortex yarns

Table 3—ANOVA results for packing density as dependent variable

Source	Sum of squares	Degree of freedom (df)	Mean square	F	Sig.
Corrected model	902.195[a]	2	451.098	20.406	0.000
Intercept	17951.864	1	17951.864	812.091	0.000
Spinning system	902.195	2	451.098	20.046	0.000
Error	265.269	12	22.106		
Total	19119.328	15			
Corrected total	1167.464	14			

[a]R squared = 0.773; Adjusted R squared = 0.735.

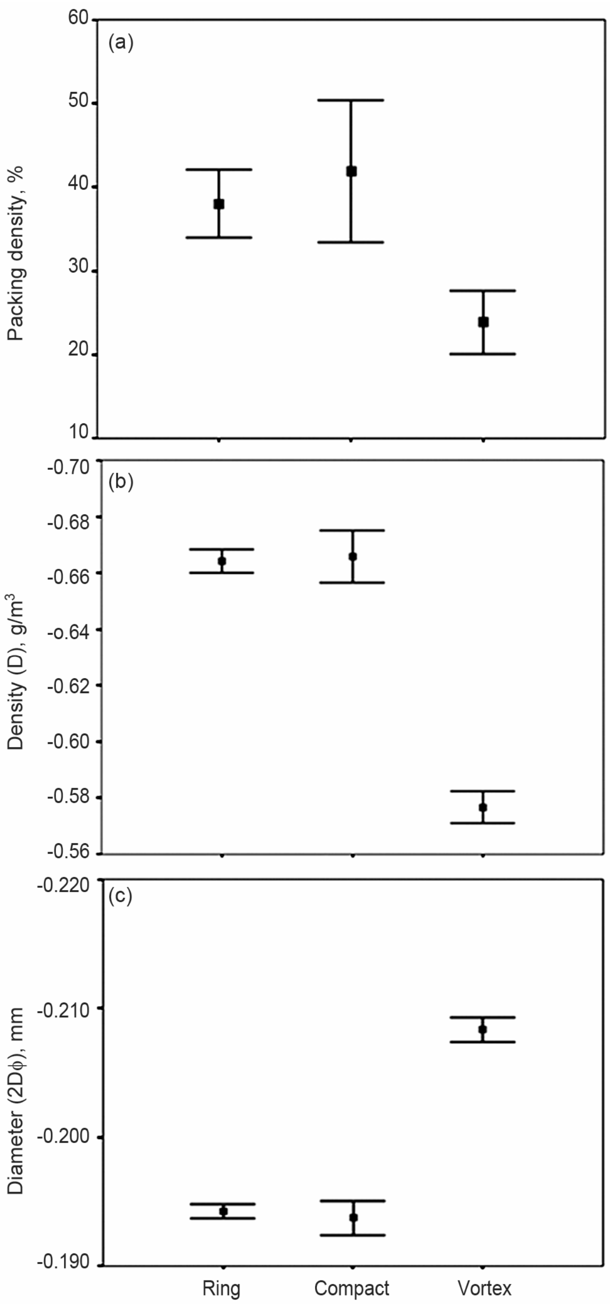

Fig. 4—95% confidence intervals for (a) packing densities, (b) density, and (c) diameter of ring, compact and vortex yarns

Table 4—Pairwise comparison for packing density as dependent variable

Spinning system (I)	Spinning system (J)	Mean difference (I-J)	Standard error	Sig.
Ring	Compact	-3.896	2.974	0.215
	Vortex	14.154*	2.974	0.000
Compact	Ring	3.896	2.974	0.215
	Vortex	18.050*	2.974	0.000
Vortex	Ring	-14.154*	2.974	0.000
	Compact	-18.050*	2.974	0.000

* The mean difference is significant at the 0.05 level.

researches who has reported that ring and compact yarns have no difference by means of breaking elongation, unevenness or imperfections[24, 25, 28].

In order to evaluate the packing density of a yarn, parameters such as density (D, g/cm^3) or diameter (2DØ, mm) values which are measured by Uster tester could be used. In this study, density and diameter values of yarns were also measured to investigate the relationships between the yarn packing density and these parameters. In general, measuring density and diameter of a yarn by the aid of a device such as Uster tester could be mentioned as a simple and practical process. On the other hand, measuring the packing density could be described as a more difficult and time consuming process, because of the stages such as sectioning, visualizing and calculating. Density and diameter values of 100% Tencel LF ring, compact and vortex yarns are shown in Table 2. Also, 95% confidence interval graphics of density (D, g/cm^3) and diameter (2DØ, mm) values are given in Figs 4(b) and 4(c).

As it is observed from Table 2 and Figs 4(b) and 4(c), density and diameter values are found correlated to packing density values [Table 2 and Fig. 4(a)]. The packing density and density values for ring and compact yarns are similar and higher than that of vortex yarns because of different spinning technologies. On the other hand, diameter values for ring and compact yarns are similar but lower than vortex yarns. Moreover, differences between the ring and the compact yarns are not statistically significant for packing density, density and diameter values. However, differences between ring-vortex and compact-vortex yarns are statistically significant for these values.

4 Conclusion

Results show that the compact yarns have the highest packing density, while vortex have the lowest. On the other hand, statistical analysis shows that the differences between the packing densities of ring and compact yarns are not statistically significant.

In this study, density (g/cm^3) and diameter (mm) values of a yarn have also been measured using Uster Tester 5. Results show that density and diameter values are correlated to packing density values. For further studies, analysis of relationships between packing density and density/diameter values will give an important information for researchers and spinning technologists to predict packing density value from the yarn density or diameter values that could be measured easily.

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