Examination of hairiness changes due to washing in knitted fabrics using a random walk approach

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Abstract

The relaxation of knitted fabrics is usually described in terms of dimensional changes of knitted loop widths and heights or fabric widths and heights, respectively. Due to washing, however, additional changes in the optical appearance and the haptic properties of a knitted fabric can occur, such as a change in the regularity or the hairiness. This article uses the random walk statistical approach to estimate the structural complexity of knitted fabrics directly after production and up to 10 washing cycles and shows that the Hurst exponent, resulting from the random walk process, is partly related to the cover factor of the knitted fabrics under investigation; however, it depicts significant contributions of the hairiness. Thus, this novel approach offers a quantitative measure of structural changes in

knitted fabrics which cannot be described by cover factor or dimensional changes.

Keywords

Knitted fabric, washing relaxation, structural complexity, random walk

Introduction

The dry, wet, and washing relaxation of knitted fabrics is an important factor for producers of knitted garments and other knitted textiles, since the dimensional change must either be taken into account for tailoring a fabric, or finishing processes are needed to avoid the expected dimensional changes. Thus, several articles report on measurements of changes in fabric width and height[1-10] or give theoretical / mathematical descriptions of the relaxation,[11-17] depending on materials and structures.

The hairiness, however, as an important factor for the optical as well as the tactile appearance of a garment or another fabric,[18] has seldom been examined during washing relaxation. While the influence of yarn hairiness on the properties of the resulting knitted fabrics has been reported in the literature,[19,20] only few papers investigate and quantitatively express the change of surface roughness or hairiness due to washing.[4,21] Several groups have examined the hairiness of yarns;[22-28] however, only few studies deal with the examination of fabric hairiness[29,30] or undesirably broken fibers in technical textiles[31] by image processing methods or other optical methods, such as laser diffraction.[32] Nevertheless, different image processing methods are already used e.g. in the determination of fabric defects, such as Fast Fourier Transformation[33], wavelet analysis[34] or Hough transformation.[35]

This article thus aims at describing yarn hairiness by a newly developed mathematical method based on numerical evaluation of the optical images of fabrics. The so-called random walking approach is used to evaluate single-face knitted fabrics created from five different yarns during 10 washing cycles. The results of this method are compared with dimensional measurements of the knitted loop widths and heights during washing relaxation.

Experimental

Five different yarns were used to create single jersey fabrics (i.e. knitting on only one needle bed of a flat knitting machine, using each needle) of 100 wales x 100 courses on a flat knitting machine CMS 302 TC (Stoll) with a machine gauge of E8 (stitch cam setting NP = 12.5, carriage speed 70 cm/s, one system): aramide (550 dtex), ultra-high-molecular-weight polyethylene (UHMW-PE, 440 dtex + 220 dtex), high tenacity polyester (1100 dtex), viscose (2 x 330 dtex), and a blended fiber with 70 % polyacrylonitrile (PAN) and 30 % new wool (WV) (Nm 30/2, mean fiber length 42 mm, CV 40 %). These materials were chosen as examples of technical yarns which can be used in protection clothing and common yarns for clothing.

In a household washing machine, 10 washing cycles were performed with heavy-duty detergent without softener at 60 °C, with a subsequent spin cycle at 1200 min^{-1}. The samples were dried on a flat, smooth surface at room temperature for min. 24 hours before measurements.

One day after production as well as after each washing cycle, microscopic images of the relaxed knitted fabrics (without any forces acting on them) were taken using a VHX-600D microscope by Keyence with the VH-Z20R objective and nominally 20 times magnification. These pictures were used to calculate the knitted loop widths and heights before washing and after each washing cycle. On the other hand, the identical pictures were transformed into 1-bit black-and-white images using CorelDRAW® X5, transferring them into line graphics with a constant threshold value of 128, with a value of 0 resulting in a nearly completely white and a value of 255 in an almost completely black picture. On the *black* parts of these images only, the so-called random walking experiment without memory was performed.[36] For this, starting from a random point chosen in the black depicted textile, a defined number of steps *t* is carried out, each of which can be directed up, down, left, or right with the same probability. The starting point and end point will differ by a certain distance. This procedure is depicted exemplarily in Figure 1(a) for *t* = 200 steps (marked red) and *t* = 2000 steps (marked yellow and blue), respectively.

Next, after 1000 repetitions, for the given starting point, the average distance *R(t)* between starting and end point is calculated, and the procedure is repeated for an increased number of steps (*t*+1) until a reasonable limit, equal to the image width (in pixels), is reached. The test is repeated for 1000-10000 randomly chosen pixels.

The Hurst coefficient *H* is calculated due to the formula $< R^2(t) >= At^{2H}$ with a constant A

(for a more detailed description with textile-related examples, cf. Refs. 37 and 38). This process is performed by linear fitting to $\log\left(<R^2(t)>\right)$ vs. $\log(t)$ dependence, as it is shown in Figure 1(b). The Hurst exponent always equals 0.5 for a completely filled black area. Areas which have significantly disturbed shape lead to widely distributed values.[39] For example, values of $H < 0.5$ mean that after one step in a defined direction, the next step in this direction is less probable than the step backwards, resulting in a smaller average Hurst exponent values (see Figure 2). This effect occurs in fine fibers where steps along the fiber axis are more probable. Therefore, the Hurst exponent H can be decreased by increasing sample hairiness[23] and increased by increasing cover factor.

As an example, Figure 3 shows the transformation from the original microscopic picture of a UHMW-PE single jersey knitted fabric after 1 washing cycle (top panel) into a monochromatic image (middle panel) and the resulting Hurst exponent distribution for 1000 tests. As expected, the Hurst distribution shows slightly smaller values than $H = 0.5$, with a strong maximum, however, around the Brownian motion regime ($H = 0.5$), since there are not so many single fibers / hairs visible.

Results and Discussion

Figure 4 shows Hurst exponent distributions for single jersey fabrics knitted from different materials, calculated from microscopic pictures taken after production and after 10 washing cycles (see insets). The Hurst exponent distributions differ significantly before and after washing, with broader distributions directly after production and sharper maxima around H ~ 0.5 after washing. This effect is quite considerable for the aramide knitted fabric, which shows almost no peak around H ~ 0.5 for the state before washing. For some of the samples, the changes in the Hurst exponent are much more significant than the deviations in the fabric pictures which can be identified by eye – apparently, the Hurst exponent distribution offers here a possibility to describe even quantitatively a change in the fabric appearance after washing.

In order to examine how strong the changes from one washing cycle to the next are, Figure 5 shows exemplarily the Hurst exponent distributions after 1, 2, 5, and 10 washing cycles. Comparing these four figures, it is harder than in Figure 4 to state which differences are significant.

Thus, the mean values for all measured Hurst distributions have been calculated. The results can be found in Figure 6 (left panel). For all knitted fabrics other than viscose, a jump of the average Hurst exponent after the first washing cycle is visible. For higher numbers of washing cycles, most samples show relatively constant values, while the PAN/WV curve has a significant rounded maximum, followed by a small dip. To discuss the jump, the one-sample t-Student test was used to examine if the Hurst exponent value calculated for $n = 0$ belongs to the population of Hurst exponents calculated for $n = 1,..., 10$, where n is the number of the washing cycles. The t-Student statistics values t_{Stud} equals $(x_0 - x)/s_d$, where x_0 is the Hurst exponent value calculated for $n = 0$, x is the mean of the population (Hurst exponents calculated for $n = 1,..., 10$) and s_d is its standard deviation. There are 10 elements in the population, hence the number of degree of freedom was chosen as 9. The one tail test was performed at 5% level of significance and the t-Student threshold value was equal to 2.3. Results are presented in Table 1. The significant increase in the Hurst exponent value after the first washing cycle was performed are observed for aramide, UHMW-PE, Polyester and PAN/WV data.

Figure 6 (right panel) shows the cover factors of the knitted fabrics under examination, calculated from the same monochromatic pictures as used for the Hurst exponent tests. The cover factor defines the fraction of a plane which is filled by the textile material, i.e. the number of black pixels in a picture, divided by the overall number of pixels. Firstly, it can be recognized that the absolute value of the cover factor is not directly correlated with the average Hurst exponent. While, e.g., viscose always shows relatively low values, the jump of the average Hurst exponent after the first washing cycle is not reproduced in the cover factor. On the other hand, the significant form of the washing cycle dependent average Hurst exponent of PAN/WV can also be discovered in the cover factor. To examine the correlation between the average Hurst exponent and the cover factor, the standard Spearman's rank correlation coefficient was calculated for each material.[40] At 5 % significance level and for 11 elements in the sample, the one tail Spearman's coefficient threshold value equal to 0.54. The results are presented in Table 2. The significant correlation was recorded for aramide, UHMW-PE and PAN/WV data. For Polyester and Viscose one cannot reject the null hypothesis stating no correlation. The same results were calculated using the Pearson as well as the Kendall's τ correlation coefficient and tests accordingly. As theoretically expected, the Hurst exponent is not only a measure of the cover factor or the hairiness, but apparently combines both fabric parameters.

For the completion of the washing relaxation experiments, Figure 7 shows the knitted loop dimensions, detected from the microscopic pictures, as a function of the number of washing cycles. For all samples, knitted loop widths and heights show a tendency to decrease on average with the increasing number of washing cycles; however, for most samples the errors are too large to allow this trend being statistically significant. The large error bars on the aramide values are related to strong deviations in the fabric between large and small loops or open and nearly fully-covered areas, respectively. The jump after the first washing cycle which is visible in the Hurst exponent cannot be reproduced by these measurements.

Conclusions and Outlook

From the experiments performed in this study, we can conclude that there are several measures of different parameters during knitted fabric relaxation:

- Average knitted loop dimension –→ fabric construction, appearance of knitted loops
- Standard deviation of knitted loop dimension → irregularity of fabric construction
- Average Hurst exponent → cover factor and hairiness of fabric

- Standard deviation of Hurst exponent → optical irregularity of cover factor and hairiness

Therefore, the Hurst exponent adds two new quantitative measures for the description of knitted fabrics related to the cover factor and the yarn hairiness. It should be noted that the method used here has to be modified for samples with higher cover factors, in order to "see" the hairs on the monochromatic images. Additionally, for a quantitative description of the hairiness using the Hurst exponent, the influence of the cover factor must be known. A simple, but time-consuming method uses a comparison of the original monochromatic picture with an artificially smoothed picture (without hairs).[37]

Opposite to usual textile hairiness measurements which are normally based on yarn measurements or on subjective tactile tests, the article shows results of the newly developed method to calculate the Hurst exponent distribution from monochromatic pictures of single-face knitted fabrics. Comparisons with cover factors, knitted loop heights and widths show that the Hurst exponent is able to give further information about the fabric hairiness, which, however, can only be interpreted quantitatively by extracting the influence of the cover factor.

Future examinations will thus concentrate on separation of the superposed effects and on improvement of the microscopic pictures to allow for examination of fabrics with higher cover factors.

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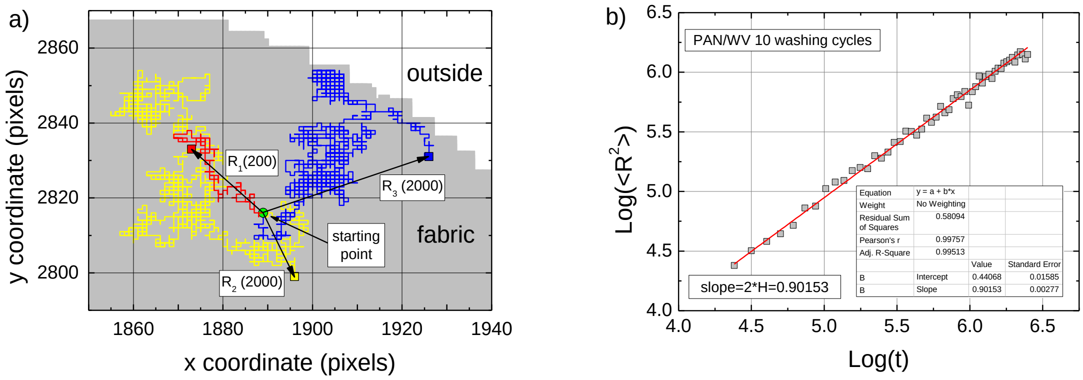

Figure 1. Sketch of 3 exemplary random walks with 200 and 2000 steps as well as the respective distances R_1, R_2, and R_3, respectively, between the starting and end points (a); double-logarithmic plot, log(*R*(*t*)) vs. log(*t*), with linear fit providing a value of Hurst exponent (b). Significantly large number of steps (R_2 case) do not warrant adequate large distances, while in some cases (R_3 case) it can sense a fabric edge, for a randomly chosen starting point.

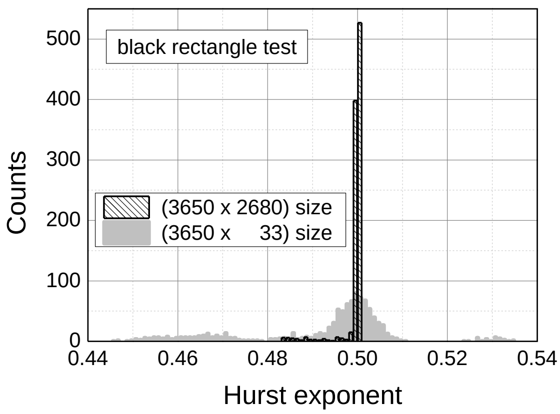

Figure 2. Random walking test for completely filled black rectangles as two-dimensional objects. Areas with a reduced width lead to values of Hurst exponent significantly different from 0.5.

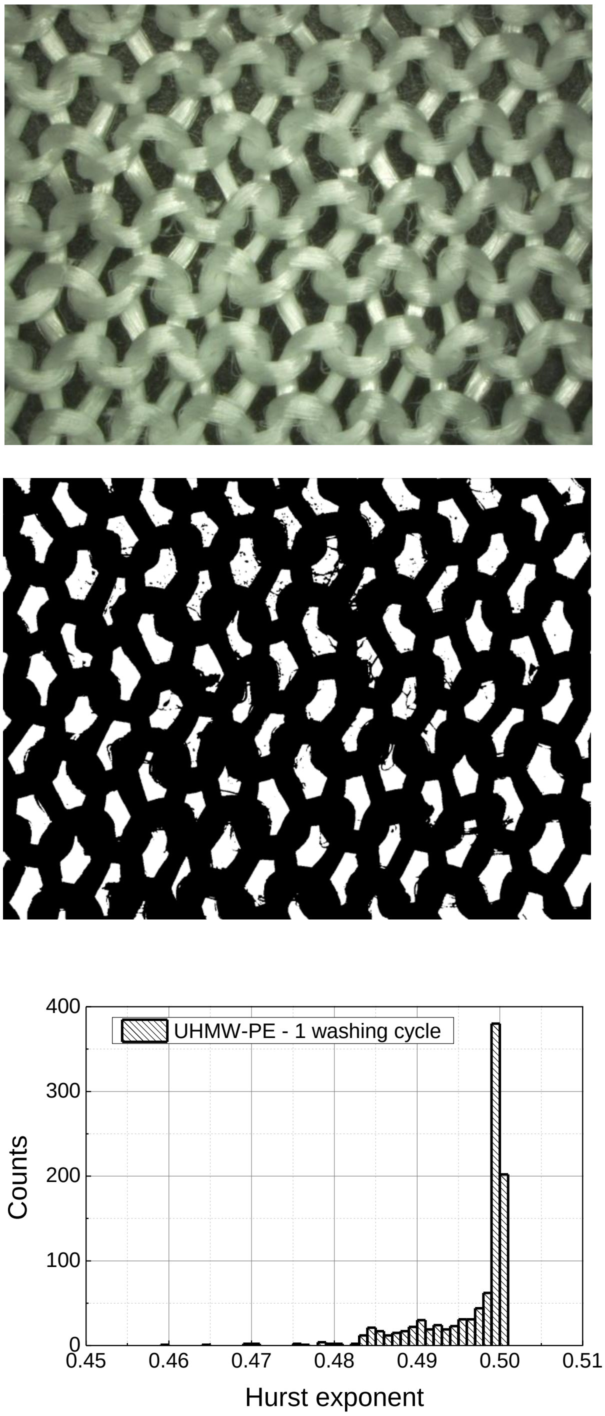

Figure 3. Transformation of a microscopic photograph of a UHMW-PE single jersey knitted fabric after 1 washing cycle (upper panel) into its monochromatic representation (middle panel) and resulting calculation of its Hurst exponent distribution (lower panel).

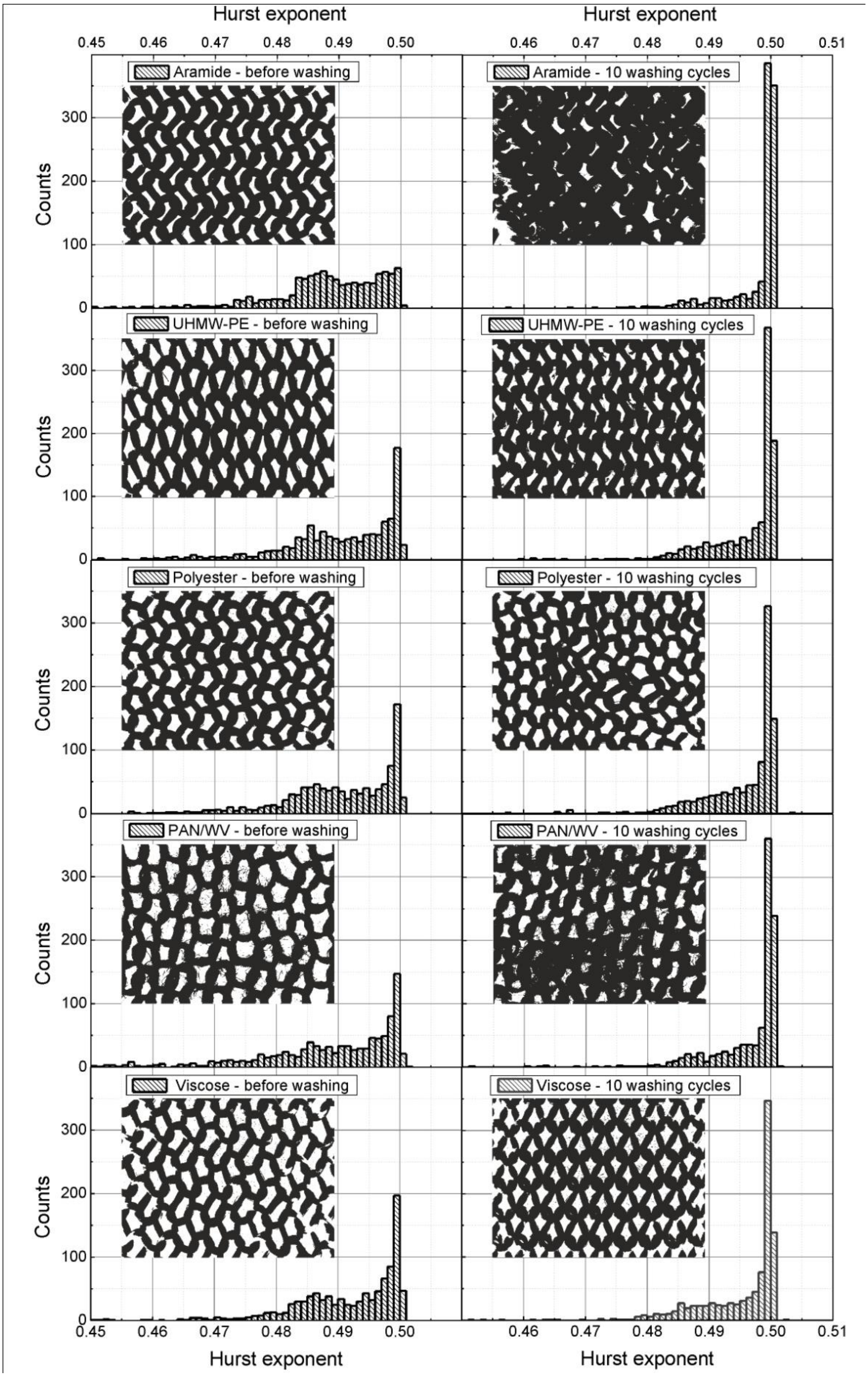

Figure 4. Hurst exponent distributions for single jersey fabrics knitted from different materials, calculated before washing (left column) and after 10 washing cycles (right column), and respective monochromatic pictures (insets). The scales are identical in all graphs.

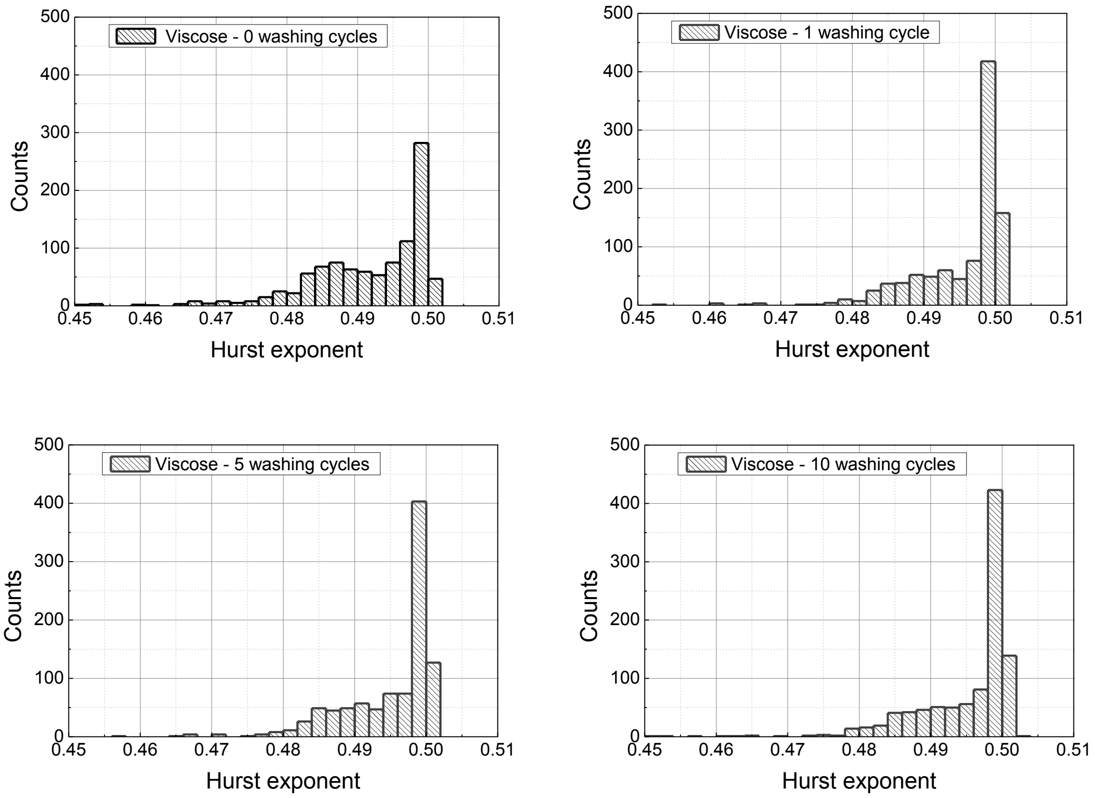

Figure 5. Hurst exponent distributions for single jersey fabrics knitted from viscose after different numbers of washing cycles. Please be aware that the binning (the width of the histogram bars) differs from Fig. 4.

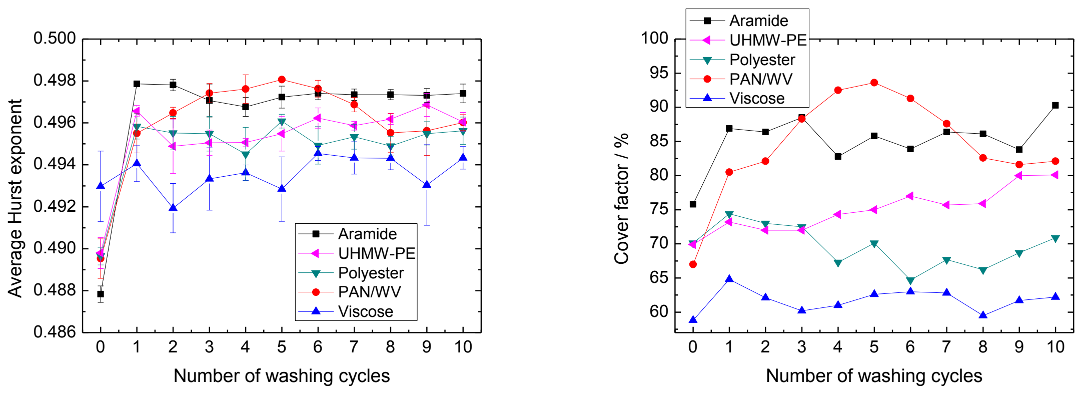

Figure 6. Average Hurst exponents for single jersey fabrics knitted from different materials, calculated for 0-10 washing cycles, error bars result from splitting the 1000 single random walks in four sets of tests (left panel); cover factor, optically detected for 0-10 washing cycles (right panel).

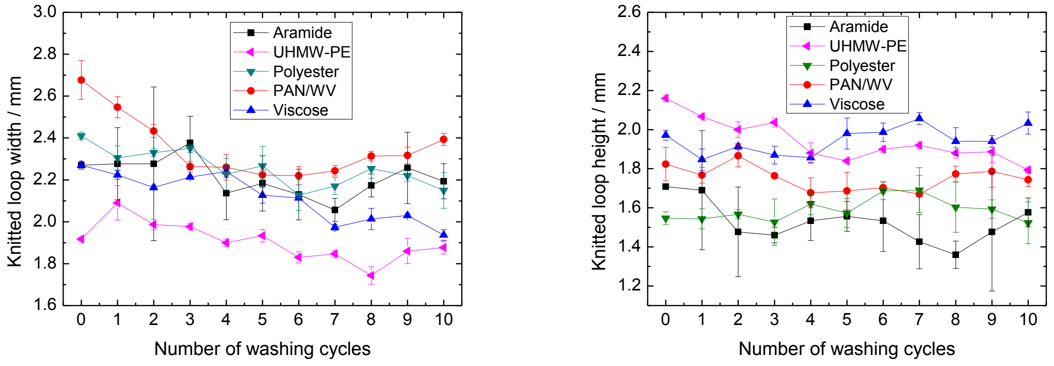

Figure 7. Knitted loop width (left panel) and height (right panel), detected from microscopic pictures, as function of the number of washing cycles.

Table 1. Significance test of the increase of the Hurst exponent value after the first washing cycle

Sample	t-Student statistics	Significant increase of Hurst exponent
Aramide	29.8	yes
UHMW-PE	8.9	yes
Polyester	12.2	yes
PAN/WV	7.3	yes
Viscose	0.8	no

Table 2. Correlation test between Hurst exponent data and cover factor data

Sample	Correlation coefficient	Significant correlation
Aramide	0.58	present
UHMW-PE	0.74	present
Polyester	0.30	absent
PAN/WV	0.93	present
Viscose	0.39	absent