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# Sustainable Aspects of Multiple-Use Woven Fabric in the Hospital Environment: Comfort and Textile Dust Generation Perspectives

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**Abstract:** Textile dust released from hospital textiles is a considerable food source for pathogenic microorganisms and can lead to infections and illness in patients and medical staff. In addition, it often causes malfunctions in sophisticated medical equipment. The structural parameters of the fabric, such as the raw material composition, the thread density and the fabric weave, can influence the amount of dust produced. Friction between threads in a woven fabric plays a crucial role in dust generation, and friction is influenced by the surface structure of fibres, yarns and fabric. Understanding these factors can help in the development of fabrics with lower release of textile dust, which can reduce the risk of spreading infections in healthcare facilities. In this paper, the influence of the washing cycle on the change in morphological properties of fabrics in satin weave made of cotton–polyester blends was investigated. The study showed that as the number of maintenance washing cycles increases, the waviness, roughness and average amplitude of the surface roughness profile of the wove fabrics increases. Damage to the fibres during washing results in dust release, with synthetic fibres releasing less dust than cotton fibres. These results provide important information about the change in fabric properties during the washing process, which may be useful for further research and development of materials for use in a hospital environment.

**Keywords:** release of textile dust particles; morphological properties of the fabric surface; satin weave; washing cycles

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## 1. Introduction

Textiles are widely used material in the hospital environment and it is extremely important that they do not transmit pathogenic microorganisms to patients or healthcare workers. Exposure to pathogenic microorganisms can lead to infectious diseases, infections, allergies or asthma [1–4]. The most common sources of pathogenic microorganisms that can lead to infections in healthcare facilities are patients, staff and contaminated equipment.

Textile dust also plays an important role as a carrier of microorganisms, which is released into the air during use due to friction between contact surfaces and fibres themselves, and is deposited in the hospital environment, leading to overall and biological air pollution [5–7]. Due to their chemical composition, textile dust particles provide a favourable substrate for the growth and development of microorganisms and pose a risk of spreading infections [4,8,9]. The airborne spread of microorganisms from contaminated medical textiles poses a great risk to operating theatre cleanrooms, but is also not negligible in textile warehouses [10,11]. Microorganisms are usually airborne in two ways, both of which are due to the physical activity of the user: directly (through the release of deposited particles) and indirectly (through the interaction between the fibres of the clothing, the user's skin and other contact surfaces) [12,13]. Duguid and Wallace [14] studied the release of dust particles as bacterial carriers from the skin and clothing resulting from users' physical activities. In their study, they concluded that the intensity of the activity studied led to a ten-fold increase in the emission of dust particles and thus the transmission of bacteria itself.

Besides the risk of infection, textile dust particles pose a significant threat to sophisticated medical equipment, as their accumulation can lead to equipment malfunctions.

Textile materials made of cotton fibres release larger amounts of dust particles than those made of fibres of a synthetic origin, but synthetic ones remain longer in the environment due to their non-degradability [15–17]. The amount of textile dust produced can be reduced by choosing a suitable raw material composition and by optimising the structural and morphological characteristics of the fabrics such as yarn fineness and crimp, fabric density and weave of the fabric. The surface of the fabric wears out with use and care, resulting in the release of textile dust [18,19].

Flinčec Grgac et al. [19] investigated the release of textile dust from cotton fabric and cotton–polyester-blend fabric before and after multiple washing cycles. It was found that the samples from the cotton–polyester blend (65/35) released significantly less textile dust compared to the 100% cotton fabric, considering the total number of particles. Furthermore, an increase in the number of dust particles released was observed with an increase in the number of washing cycles, especially those with a size of 3 to 5 µm, while the number of larger particles with a size of 10 to 25 µm or higher decreased significantly. Based on statistical indicators, it was found that the tests must be performed after a larger number of washing cycles [20]. In recent decades, the problem of textile dust and its impact on health has been studied by a small number of scientists [21,22]. With the aim of reducing the release of textile dust and, consequently, preventing the spread of disease in the hospital environment, Malinar, et al. studied the influences of various fabric parameters on the textile dust generation, at the micro and macro levels [21]. Friction, as the result of the physical and chemical reaction of two substances in contact, is an essential feature both in the manufacturing of linear and flat textile products and in their subsequent use. The coefficient of friction of the fibres influences the behaviour of the fibres during drawing and is a crucial parameter for achieving the appropriate strength, lustre and hairiness of the yarn. The frictional properties of textile fibres play an important role in the yarn spinning and processing and depend on various factors such as the raw material composition, surface properties, pressure between two surfaces, temperature, humidity, contact area and absorbency. When a fabric is subjected to an external load, energy is released through various mechanisms, including elastic energy due to the stretching of the yarn, friction between yarns in the fabric and kinetic energy due to the transfer of force momentum to the yarns [22–24]. The friction between yarns allows the stress transfer within the fabric and restricts the yarn movement through contact with adjacent yarns. The coefficients of friction at the various contact points of the threads in the fabric and the frictional properties of the fabric surface affect the tactile properties. All these factors contribute to the overall comfort of the fabric.

The stick-slip phenomenon is a frequently observed phenomenon in friction tests on fabric structures [24]. This phenomenon occurs when the velocity of the contacting body oscillates between zero and a certain finite value. For the stick-slip phenomenon to occur, the coefficient of friction must be variable. This mean that the static coefficient of friction, which represents the minimum force required to set the body in motion on the surface, must be greater than the kinetic coefficient of friction, representing the force opposing the body's motion on the surface. Additionally, the system must be flexible enough to allow changes in the velocity of the sliding body. The microstructure of the fibre surface can cause variations in the frictional resistance due to surface irregularities. This can lead to a change in the speed of the sliding body and thus influence the stick-slip phenomenon, regardless of the frictional behaviour of the surface. Higher values of static friction can lead to a higher initial modulus or bending stiffness and greater hysteresis. At the level of the yarn and interlacement points in the fabric system, the presence of different-sized fibrils can result in variations in local friction. The surface roughness of the yarn or fabric has a greater influence on the overall friction than the roughness of the fibre surface. At the interlacement points of the yarns in the warp and weft system, there is real contact

between the fibres with friction at the micro and meso level, which influences the stick-slip phenomenon at the yarn level.

When the fabric is subjected to external mechanical stress, deformation occurs, causing thread displacement within the structure and thread-to-thread friction [25]. The displacements are more pronounced in knitted structures than in woven ones. Woven structures have a grid-like structure and two main axes of symmetry running in the warp and weft direction. Stretching the woven fabric can lead to zero or minimal thread sliding, but any deformation of the thread results in the stick-slip phenomenon occurring during bending and shear deformations of the fabric. Bending resistance is supported with a combination of tensile and compressive stresses that occur on opposite sides of the fabric plane. The bending of textile material is therefore a complex phenomenon involving several types of deformation such as tensile, bending, shear and compressive deformations. As all of these are relative movements on a microscopic or macroscopic level, it is clear that friction has a significant influence on the behaviour of the fabric (Figure 1).

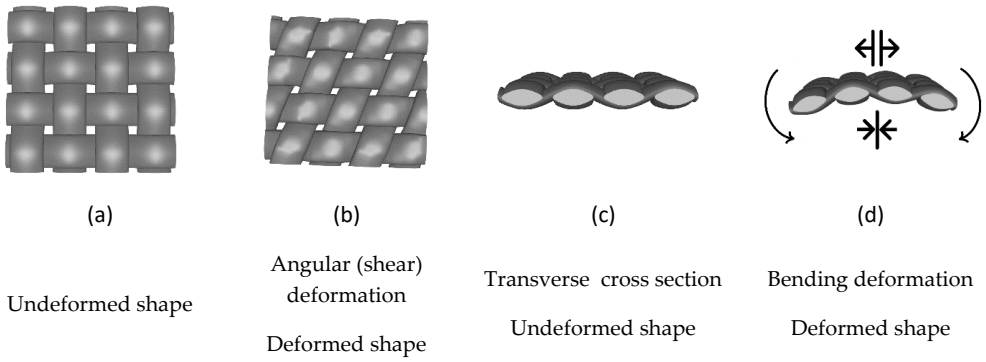



**Figure 1.** Effect of friction on fabric behaviour: (**a**,**c**) undeformed shape; (**b**,**d**) deformed shape.

In use, woven products are subjected to various stresses that can occur outside the main symmetry axes (warp and weft). The occurrence of a shear load (angular load) leads to angular deformation and deformation of the fabric transverse cross-section. This form of deformation is complex, important for clothing fit, comfort and deformability and is often overlooked as standard fabric testing usually includes testing properties only in the main directions. The initial angular deformation of the fabric is made possible with the twisting of the warp and weft threads at the point of intersection, and friction at the point of contact plays an important role in the mechanical behaviour of the fabrics and the release of textile dust.

However, the shape of the contact area and the stress distribution in it are usually unknown, which makes it difficult to predict the friction at the intersections of the warp and weft yarns during angular deformation.

In staple yarns containing twists, the tensile stress leads to the occurrence of lateral stresses, causing changes in the geometry of the yarn axis and a deformation of the transverse cross-section of the yarn and the fabric structure. This leads to the occurrence of normal forces in the yarn cross-section. The deformation of the woven fabric in any weave is influenced by friction between fibres and yarn-to-yarn friction. The friction and the stick-slip phenomenon have an anisotropic character. At the fibre level, the preferential orientation of the molecules on the surface contributes to the anisotropy. At the level of the yarn, the structure itself exhibits anisotropy because the fibre bundles are preferentially aligned in the direction of the longitudinal axis of the yarn. The angle between two yarns in contact affects the coefficient of friction. In a woven fabric, the yarn systems are perpendicular to each other, so the properties of such a material are likely to be mirror symmetrical to the two major axes, i.e., orthotropic.

Surface roughness is a very important property for the tactile properties of fabrics used in hospital environments, hygiene products, protective clothing and bedding that must

meet certain demands when in contact with the user. Roughness is defined as the vertical deviation of the fabric surface from its ideal shape and is used to estimate the texture of the fabric surface [26–29]. If these deviations are large, the surface is considered rough, and if they are small, it is considered smooth. It can be stated that the roughness of the fabric is one of the main reasons for the tactile sensations such as scratching, stinging, sharpness, warmth and coldness, which are the key characteristics associated with touch comfort. The surface of a textile material is described with two components of surface texture: roughness and waviness. The result of short wavelengths is roughness, while waviness is the result of longer wavelengths within the observed roughness profile [30–32]. To characterise the shape of the surface elements, a new parameter is introduced to describe the morphology of the woven fabric profile, namely the roundness of the profile ($R_{ku}$), which describes the roundness of the profile at the reference length [30]. If the Rku value is smaller than three, the peaks and valleys of the profile are flatter, i.e., the distribution function has a "flattened" shape. If the $R_{ku}$ parameter value is greater than three, the peaks and valleys of the profile are sharper, i.e., the distribution function has a "poenter" shape (Figure 2).

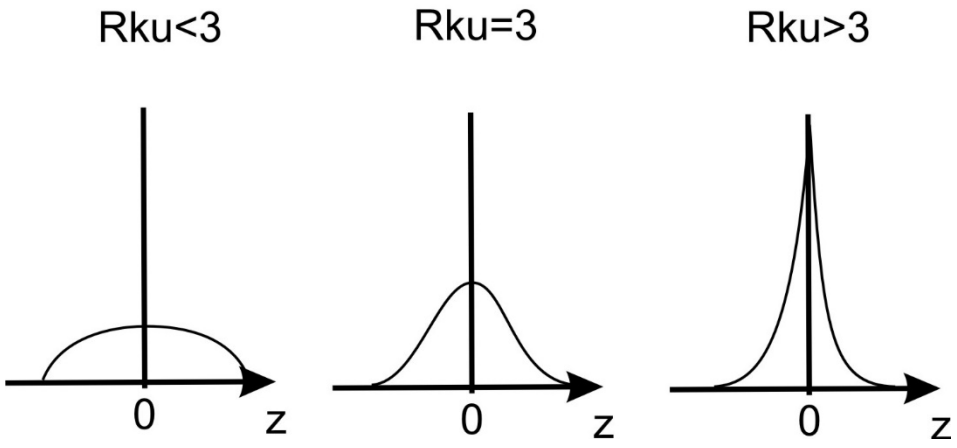



**Figure 2.** Representation of the profile roundness as a function of the $R_{ku}$ value [28].

In this paper, the influence of multiple washing cycles on the sustainability of comfort properties and textile dust generation of a cotton/polyester fabric (50%:50%) in satin weave intended for use in a hospital environment is investigated. Results show that washing cycles affect fabric properties, including surface-roughness-profile average wavelength and amplitude, bending stiffness and roundness of the profile, coefficient of friction and thermal permeability and conductivity. An increased number of washing cycles affects the release of textile dust, the behaviour of which correlates with sensorially determined changes in individual parameters measured with FTT. Looking at the results, it can be seen that the greatest changes in the fabric occur after 3 washing cycles, which show a greater influence on the release of larger textile dust particles than in the sample washed 10 times.

## 2. Materials and Methods

A fabric made of a cotton/polyester blend (50/50) (M) in satin weave A1/4 (A) was produced on a Picanol OMNIplus 800 loom (air-jet loom, width: 190 cm) at the Čateks d.o.o. textile mill, Čakovec, Croatia. The declared fabric density is 36 warp threads/cm and 26 weft threads/cm and surface mass is 183.9 g/m$^2$. The fabrics were desized, scoured and bleached according to the factory's recipes and purchased for research purposes. The tests were carried out to gain knowledge about the influence of the multiple washing cycles on certain properties of the fabric in relation to the touch and on the generation of textile dust. The samples were washed according to EN ISO 15797:2017 [33] with a standard detergent containing phosphate-free optical brighteners (WFK 88060) and ε-(phthalimido)peroxyhexanoic acid (PAP).

To assess the impact of washing on the structural properties of woven fabrics, the densities of warp and weft, as well as fabric thickness, were determined.

Warp and weft densities were determined by counting threads per centimetre five times for each sample, utilizing the DinoLite Premier portable digital microscope (AM-7013MZT), renowned for providing high-resolution, high-quality images. The average value obtained from these measurements was used for subsequent calculations.

Field emission scanning electron microscopy (FE-SEM, Tescan, Czech Republic, FE-SEM, Mira II LMU) was used to characterise the surface morphology of the samples before and after several wash cycles. Prior to imaging at FE-SEM, the samples were coated with chromium for 120 s in a steamer (Quorum Technologies, Q150T ES Sputter Coater, Laughton, UK).

Fabric thickness was measured in accordance with the HRN EN ISO 5084:2003 [34] standard, which involves assessing thickness at ten distinct locations. A DM 2000 thickness gauge manufactured by Wolf, Germany, was employed for this purpose. The instrument boasts a precision of 0.001 mm.

### *2.1. Testing with the Fabric Touch Tester SDL (Atlas, FTT M293)*

The Fabric Touch Tester (FTT M293, SDL Atlas) is a device that allows use for evaluation of the hand feel of fabrics and simultaneously measures 13 physical properties of fabrics. The device simultaneously measures surface roughness and friction properties, thermal properties, bending and pressure. The measurement is carried out in both warp and weft directions and on both sides of the tested sample (front and back of the fabric). Based on the determined values of 13 fabric indices, the FTT QC Evaluation software then calculates three primary comfort indices, namely smoothness, softness and warmth. The following measured and calculated properties are taken into account: average bending stiffness (BAR) and work at bending (BW), thermal conductivity under compression (TCC), thermal conductivity with recovery (TCR), maximum heat flux (QMAX), work at compression (CW), recovery rate after compression (CRR), average compressive stiffness (CAR), average recovery stiffness (RAR), thickness (T), surface roughness amplitude (SRA), surface roughness wavelength (SRW) and surface friction coefficient (SFC). For the FTT measurements, five samples were made in the shape of the letter "L" with the dimensions given in Figure 3, with the direction of the fabric (warp/weft) and the side of the fabric (front/back) clearly marked. Before measurement, the samples needed to be conditioned under standard atmospheric conditions of 20 °C ± 2 °C and 65% ± 4% relative humidity.

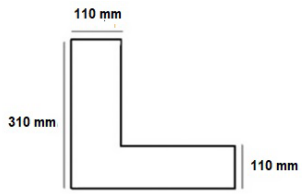



**Figure 3.** Dimensions of the test specimen.

### *2.2. Test on Laser Particle Counter LasAir III (Particle Measurement Systems)*

The amount of dust particles released from the textile sample was measured using the laser particle counter LasAir III (Particle Measuring Systems) [35]. The particle counter is connected to a particle generator located inside the cabin under laminar air flow conditions, which according to ISO 14644-1 [36] ensures very high air purity and allows testing without the influence of external particles. The test method was adopted from EN ISO 9073-10 [37] with an adapted test time of 30 min. The test specimens were tubular and have dimensions of 220 mm × 285 mm, with 5 test tubes to be tested. The textile sample was placed on the particle generator and subjected to 60 cycles of controlled torsional twisting and simultaneous compression and thus multidirectional buckling of the sample. During the generation of the particles, air was drawn from the test chamber and fed via a pipe into the particle counter. In the laser counter, the dust particles were counted and classified

according to the following size categories: 0.3 µm for particle sizes of 0.3–0.5 µm; 0.5 µm for particle sizes of 0.5–1 µm; 1 µm for particle sizes of 1–5 µm; 5 µm for particle sizes of 5–10 µm; 10 µm for particle sizes of 10–25 µm; 25 µm for particle sizes larger than 25 µm. For each sample, the measurements were performed on 5 test tubes. This method was adopted from EN ISO 9073-10 [37] Textiles—Test methods for nonwovens—Part 10: Lint and other particles generation in the dry state, with the test time adjusted to 30 min [19,20]. Due to the large number of particles released in total, the number of particles is displayed graphically in logarithmic values for easier presentation of the results.

### *2.3. Analysis of the Roughness Profile of the Samples*

To analyse roughness at multiple levels (fibre level, yarn level, weave unit level), the primary roughness profile needs to be filtered to remove unwanted components with long wavelengths from the primary profile [23]. In order to eliminate unwanted wavelength sizes from the primary profile, a cut-off evaluation is performed to obtain a filtered profile containing only wavelengths within the desired surface level. By removing the long wavelength components, what an individual perceives as roughness is defined. The curvature value from the filtered profile, i.e., the Rku parameter, was determined by processing the individual values in the OriginPro software and Surface Roughness Parameters module.

## 3. Results and Discussion

The tables and figures' representation of the results shows the changes in the morphological properties of the cotton/polyester samples in satin weave before (AMP) and after multiple washing cycles (AMP_3W, AMP_10W). The samples were tested on the FTT device in the warp direction with the sensory element of the FTT device touching the opposite to warp the yarn system and the weft system, respectively. Due to the representativeness of the results obtained by measuring on the FTT device, their mean values from measuring three test tubes of the sample are presented. In addition, the change in the total number of dust particles released from the cotton/polyester samples before and after multiple washing cycles is tracked. Since the values of the total number of dust particles released are in a wide range of numbers, they are presented as a logarithmic value of the total number of particles released, for easier and more precise presentation of the results. In this section, Table 1 shows thickness and density, Figures 4–11 provide representations of the obtained results and the changes in individual properties under the influence of multiple washing cycles are observed and discussed.

**Table 1.** Structural parameters of fabric samples.

| Parameter | AMP | AMP_3W | AMP_10W |
|---|---|---|---|
| Warp density, ends/cm | 29.2 | 30.0 | 29.6 |
| Weft density, picks/cm | 26.8 | 27.0 | 27.6 |
| Thickness, mm | 0.42 | 0.58 | 0.58 |

Table 1 shows the measured parameters of the structure of the initial sample before washing, as well as after undergoing 3 and 10 washing cycles. The results reveal alterations in warp and weft density following exposure to the washing conditions. Notably, there is a significant increase in warp density after 3 washes, followed by a decrease after 10 washes, while the weft density consistently increases with washing cycles. These findings suggest that after the initial shrinkage in the weft direction, the sample experiences elongation due to additional tensile stresses during the washing process. In the warp direction, the sample continues to shrink until the 10th washing cycle. The thickness of the sample increased by 38% after the first 3 washing cycles and remains constant until the 10th wash cycle. Subsequent research results showed how these changes affected the morphological and thermal properties of the fabric.

The images obtained with the SEM microscope (Figure 4) show the surface of fabric samples, sequentially unwashed (AMP) and washed 3 (AMP_3W) and 10 (AMP_10) times. Enlarged images on the right side allow for a visual assessment of the fibre surface on the same fabric samples. From the images, it is visible that the unwashed fabric sample has a smoother surface, and the fibres in the yarns are compact and parallelized. After three washing cycles, it is noticeable that the surface is more textured, and the fibres in the yarns are more separated from each other. It cannot be said that the structure is destroyed, but there is evident slight deformation and less order in the structure compared to the unwashed sample. At the fibre level, no change is observed—the fibre surface remains smooth and unchanged compared to the unwashed sample. In the case of the sample washed 10 times, a greater amount of protruding fibres that have come out of the yarn structure is noticed, and fibrillation on the fibres is observed for the first time.

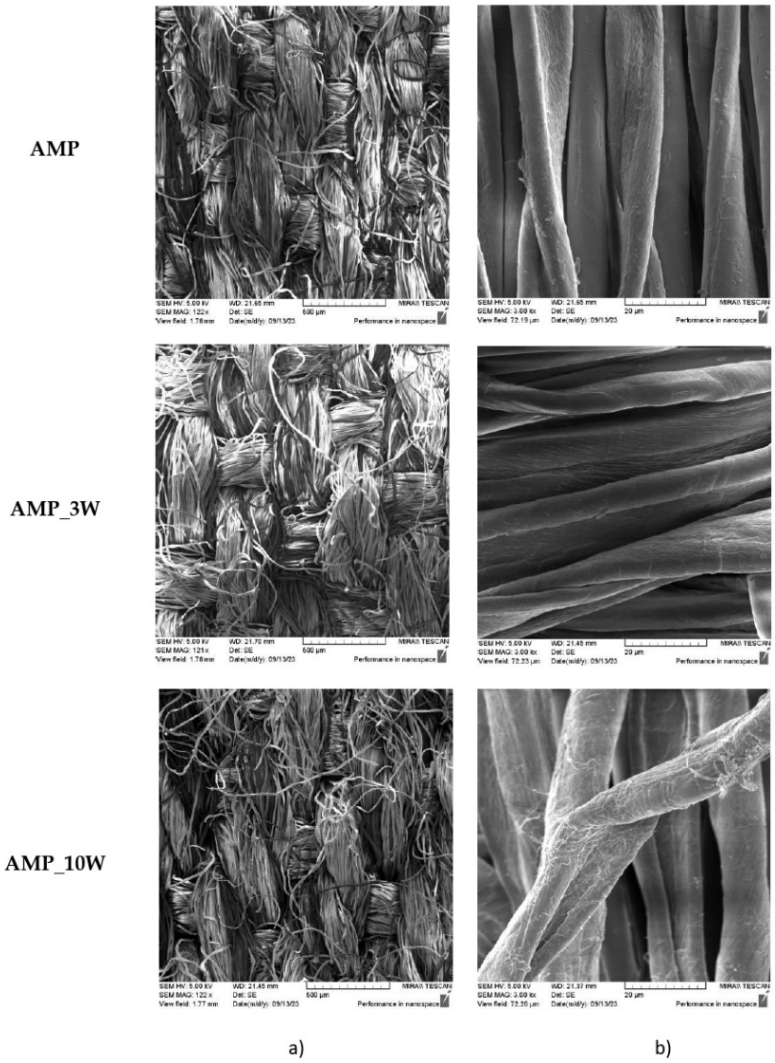



**Figure 4.** Microscopic images of the surface of the unwashed (AMP) and 3-time-washed (AMP_3W) and 10-time-washed (AMP_10W) cotton/polyester sample in satin weave, taken with a field emission scanning electron microscopy with magnification: (**a**) 800×, (**b**) 3000×.

It is important to point out that the examination of fabric surface roughness shown in Figures 5 and 6, obtained by measuring with the FTT device, was carried out in such a way that a very thin sensor passes over the surface of the material with a small force and detects any irregularities on the fabric very precisely. Considering the relatively small contact area of the sensor, the recorded profile roughness contains very detailed information about

deviations that cannot be fully detected when touching the fabric surface with fingers or other body parts. Therefore, the obtained roughness parameter results may differ from the sensory smoothness/roughness evaluations of the surface.

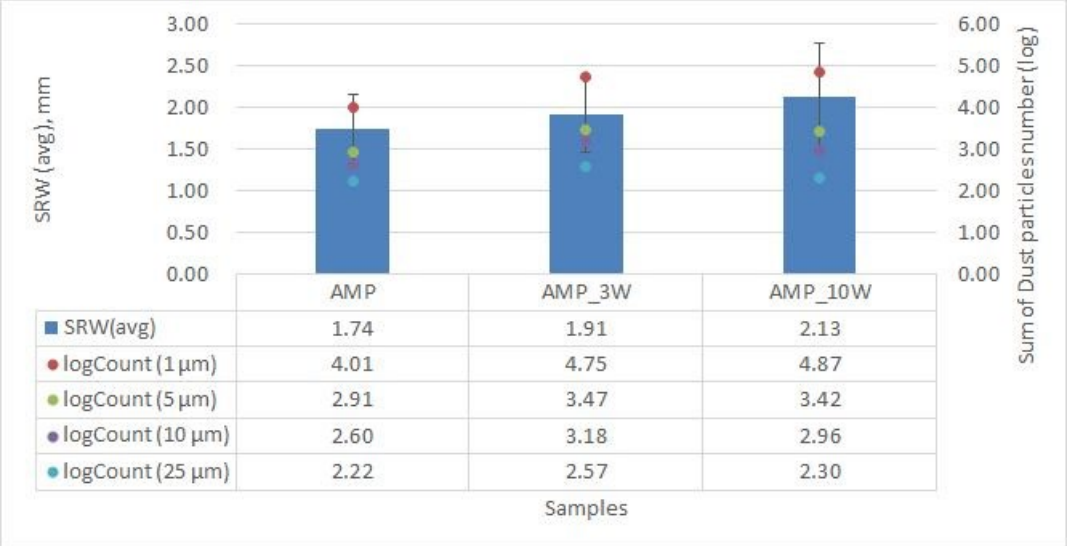



**Figure 5.** Change in the wavelengths of the surface roughness (SRW) of the sample and release of dust particles as a function of the influence of multiple washing cycles.

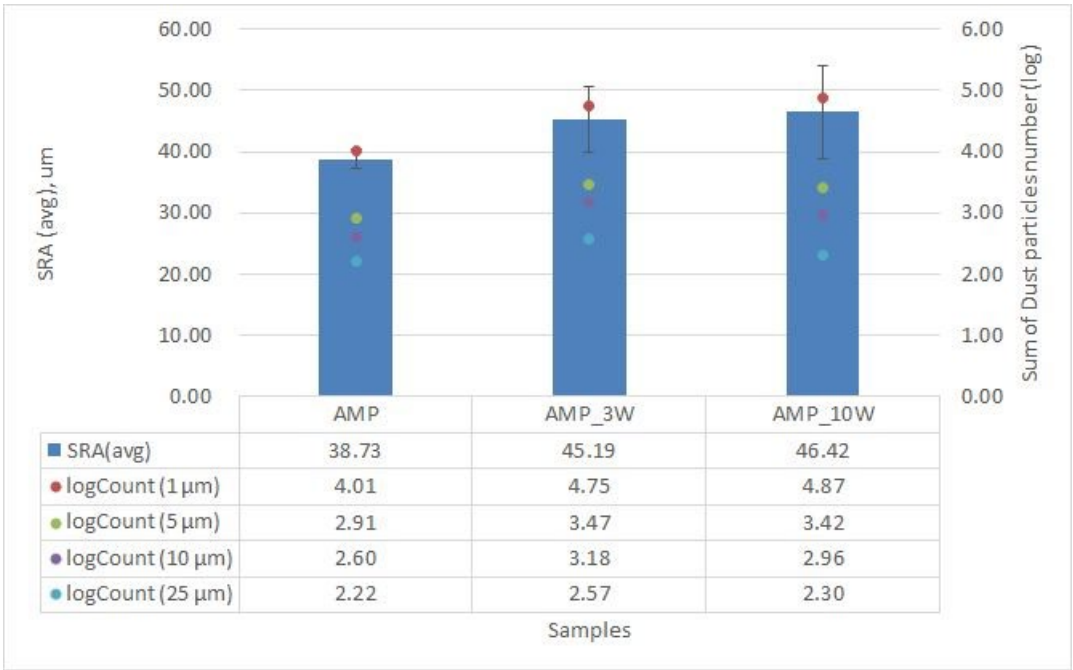



**Figure 6.** Changes in surface roughness amplitudes (SRAs) and dust particle release depending on the influence of multiple washing cycles.

In Figure 5, the columns show the average value of the wavelengths of the cotton/polyester sample in satin weave A1/4 (3) and the same sample after 3 and 10 washing cycles. Additionally, the data points indicate the change in the total number of dust particles released from the cotton/polyester samples before and after multiple washing cycles. According to the previous studies by Malinar et al. on the formation of dust particles [21,28], it is recommended to monitor particles of larger dimensions (from 5 µm to 25 µm and

larger), as it is certain that particles of these dimensions belong to individual fibres of the textile dust and not to fibres deposited on the surface of the sample due to various mechanical, chemical or thermal influences. From the results obtained and the graphical representation, it is possible to observe a linear increase in the average wavelength of the cotton/polyester sample with an increasing number of washing cycles. The initial sample has a wavelength of 1.74 mm on average, which increases to 1.91 mm after the three cycles and 2.13 mm after ten washing cycles, suggesting an increase in the surface roughness of the sample due to mechanical action during a washing cycle. Furthermore, it is evident that the waviness has a greater impact on the release of smaller-sized dust particles compared to larger-sized dust particles. As the number of washing cycles increases, the number of released small-sized dust particles (1 μm) increases, while the number of released larger-sized dust particles (from 5 μm to 25 μm) decreases, as shown in the tabulation representation of the results (Figure 3). Moreover, it is evident that the waviness is not equally correlated with larger-sized dust particles, meaning that as the effective surface area of the sample increases (surface becomes more wavy), smaller-sized dust particles tend to be trapped in the interstices on the surface and are released with more difficulty, whereas larger-sized dust particles are more easily released from the surface of the sample.

In Figure 6, the columns show the change in surface roughness amplitude values of the cotton/polyester sample in relation to the number of released dust particles. The profile average amplitude, along with the surface average wavelength, provides information about the surface morphology of the fabric sample. The graphical representation of the results shows that the surface roughness amplitude increases with the washing cycles, due to fabric shrinkage. For the initial unwashed sample, the average amplitude value is relatively large at 38.73 μm and significantly increases with the washing cycles, reaching 45.19 μm after 3 cycles and 46.42 μm after 10 cycles. The increase in profile average wavelength with the wash cycles is not as significant as the sudden increase in profile amplitude, making the fabric feel more rough and therefore less comfortable than the original unwashed sample. It can be assumed that after 3 washing cycles, the fabric slightly shrunk, and after 10 cycles, it experienced some tearing as the average profile amplitude value increased, resulting in the expansion of the sample's average weave length and elongation of the peaks. As the average wavelength increases, the surface of the sample becomes smoother, which can be attributed to the influence of the chemical and mechanical action during the washing process. It is also evident from the results presented that amplitude has a greater influence on the release of small-sized dust particles compared to larger ones.

In Figure 7, the change in the surface friction coefficient in relation to the number of released dust particles is shown. It can be observed that the coefficient of friction is corelated to the surface morphology of the cotton/polyester sample and that after 10 washing cycles, the structure of the sample becomes smoother. The surface friction coefficient correlates with the number of larger particles released. Surfaces with a higher coefficient of friction provide greater resistance to sliding and tend to retain larger particles, while smaller particles are more easily released from the surface. According to the results, due to the reduced friction caused by the change in the structure of the fabric, which was permanently altered with the action of mechanics, chemistry and heat after 10 washing cycles (Table 1), the number of released particles is reduced compared to the sample after 3 washing cycles.

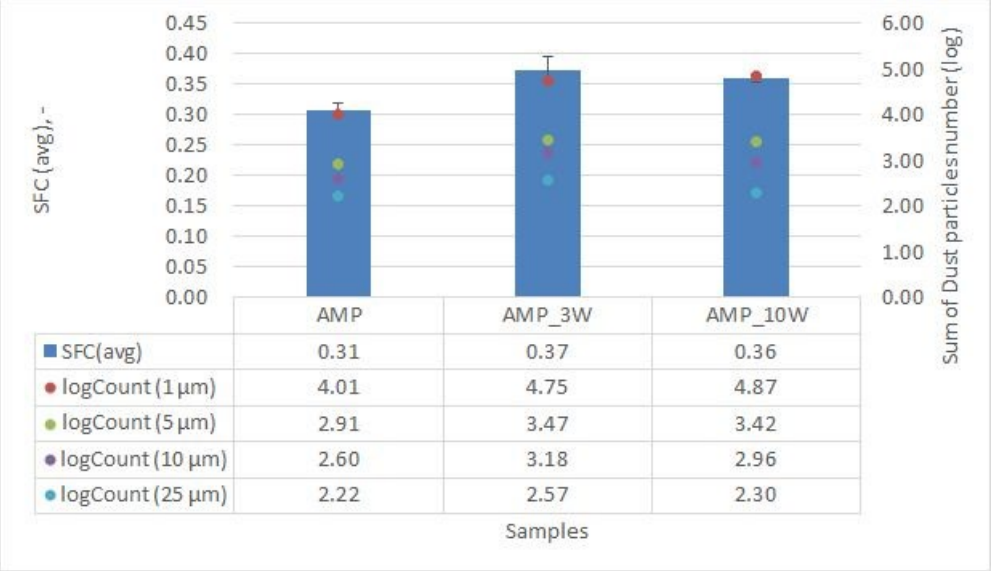



**Figure 7.** Change in surface friction coefficient (SFC) and release of dust particles as a function of the influence of several washing cycles.

Figure 8 shows the change in average bending stiffness (BAR) in relation to the release of dust particles depending on the influence of the washing cycles. From the displayed results, it is evident that the sample is more flexible in bending after 10 washing cycles. It can be concluded that the bending stiffness correlates with the dust particles size. The larger the particle size, the more the number of released particles decreases, thus leading to a higher correlation with the bending stiffness of the fabric. The number of released small-sized particles correlates more strongly with the relief (roughness) of the sample surface. As a result of the interaction between the yarn and the fibres within the yarn, particles of different sizes are separated and released. The strength of cotton material decreases during the washing process, which is a consequence of the fibre surface damage caused by chemical, mechanical and thermal action (Sinner's circle). The material damaged in this way contains many fibres on the surface itself, which can be easily separated from the surface of the material subjected to stress.

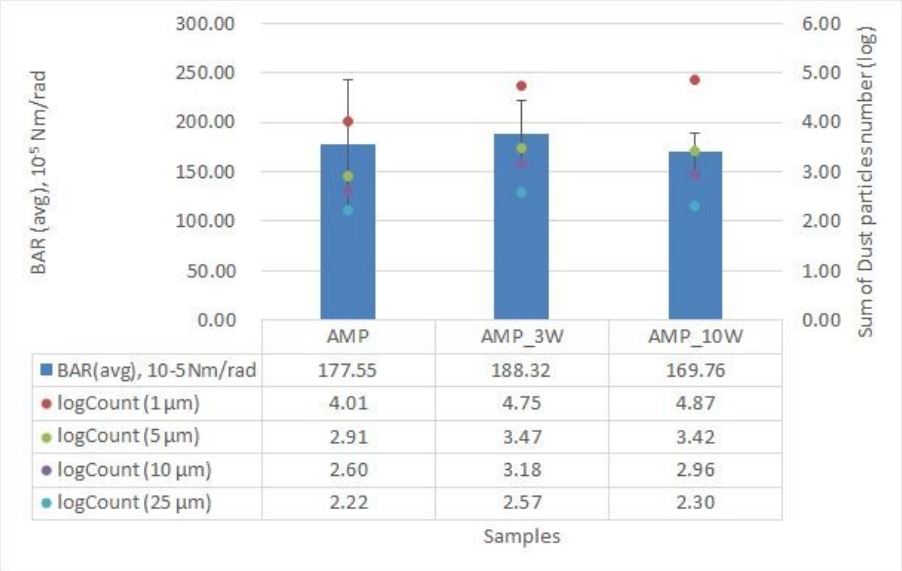



**Figure 8.** Change in the average bending stiffness (BRA) and release of dust particles depending on the influence of the multiple washing cycles.

Figure 9 graphically shows the values of profile roundness (Rku) at the weave unit level, where a smaller Rku means a rounder profile (rounded bumps also mean a smoother texture to the touch—more comfort). It can be seen that the roundness increases after 3 washes, while it decreases after 10 washes, compared to the fabric tested after 3 washing cycles. It can be concluded that the roundness of the profile is partially correlated with the coefficient of friction. The washing processes influenced by the Sinner's circle affect the properties of all elements that make up the fabric, resulting in deformations of the yarn in all directions. Fabrics in satin weave show a greater displacement of the interlacement points of the structure, so it can also be seen that the weave unit influences the release of larger-sized dust particles. Also, from Figure 8, it is also evident that the fabric sample in satin weave releases more textile dust after 3 washing cycles and its Rku value is the highest, i.e., the fabric is rougher than the initial fabric and the same after 10 washing cycles, which have a lower number of released textile dust particles, so we can conclude that the weave unit affects the amount of textile dust formation of the sample.

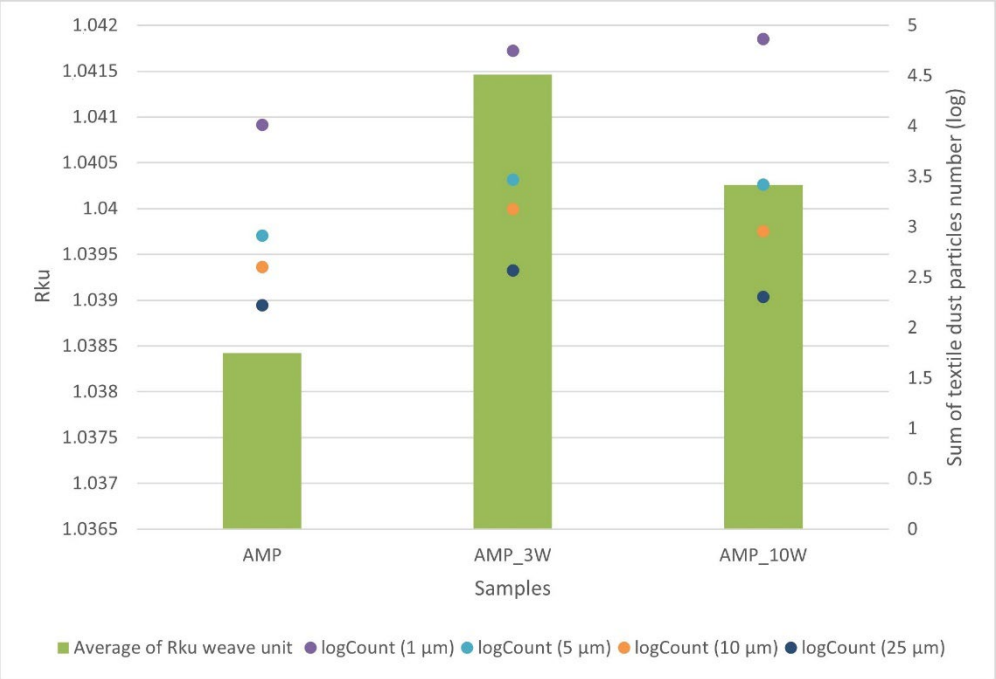



**Figure 9.** Change in profile roundness (Rku) and release of dust particles depending on the influence of multiple washing cycles.

The graph in Figure 10 shows the values of maximum heat energy (QMax) transferred through the fabric sample during compression. The graph shows that the rate of heat transfer through the fabric is highest for the unwashed sample (AMP), while the same parameter decreases with an increasing number of wash cycles, by 12.2% after 3 wash cycles (AMP_3W) and by 4.0% after 10 wash cycles (AMP_10W). This means that the thermal comfort does not decrease linearly with the number of washing cycles, which could be a consequence of the fabric surface that became rougher when exposed to multiple washing cycles. In more surface relief of the woven fabric, static air can be trapped on the surface, which may result in a lower $Q_{max}$.

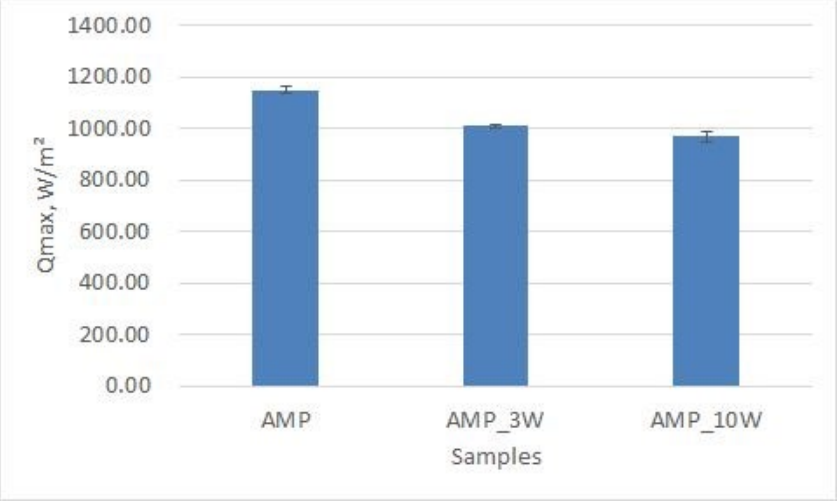



**Figure 10.** Maximum thermal energy (Qmax) transferred through a fabric during compression.

In the graph shown in Figure 11, the thermal conductivity of fabric samples during compression (TCC) and recovery after compression (TCR), also known as active thermal conductivity, is presented. The amount of thermal energy transmitted through the thickness of the sample under a compressive load and recovery changes over time with wash cycles, with the largest difference being between the unwashed sample (AMP) and the sample washed 3 (AMP_3W) and 10 times (AMP_10W). The unwashed sample exhibits the lowest ability to conduct thermal energy, i.e., it transfers the least amount of thermal energy compared to the other samples. The reason for this could be attributed to a lower number and area of contact between warp and weft threads (the unwashed sample has a lower thread density), resulting in a reduced thermal conductivity of the material. Contact points between threads provide better heat transfer through the material, while air gaps increase the resistance to heat transfer. The textile material (fibres/yarns) acts as a heat conductor and the air acts as an insulator.

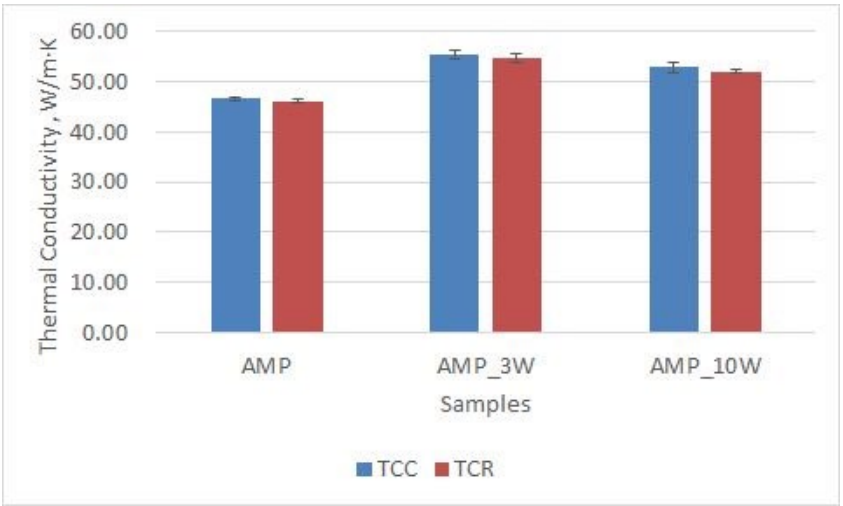



**Figure 11.** Thermal conductivity during compression (TCC) and recovery (TCR).

## 4. Conclusions

This study is focused on satin weave fabric and its response to multiple washing cycles. Satin weave fabrics, known for their smooth surface, exhibit noticeable alterations in surface roughness amplitude (SRA) and surface roughness wavelength (SRW) with increased washing cycles. This is attributed to shifts in thread density and fabric shrinkage

during washing. Washing cycles have an influence on the release of textile dust particles in a way that higher SRA and SRW values are correlating with greater dust generation. Fabric's morphological properties, particularly surface roughness, play a significant role in dust release. The fabric's bending stiffness of the satin fabric is decreasing after ten washing cycles, making it more pliable. Despite potential fibre surface damage during washing, the number of larger dust particles is decreasing after ten washing cycles compared to three cycles. The roundness of the fabric surface profile varies with washing cycles, being higher after three cycles and decreasing after ten cycles. Thermal comfort assessment reveals a non-linear decrease in heat energy transmission through the fabric after washing cycles. This is likely due to fabric shrinkage and increased thickness, resulting in reduced fabric porosity. Fabric samples in satin weave display improved thermal conductivity during compression and recovery after three washing cycles. While satin weave fabric is comfortable to wear due to its smooth surface and high pliability, it is prone to deformation with frequent maintenance processes, limiting its lifespan. As a recommendation, these fabrics are best suited for single-use applications such as wound dressings, bandages or bedding, especially in healthcare settings with stringent hygiene requirements.

The information obtained from these findings can guide future research and development efforts aimed at replacing non-woven textiles in various applications, potentially contributing to waste reduction and improved sustainability. They are also offering practical recommendations for their use and highlighting their potential in addressing sustainability concerns in various industries.

The release of textile dust from textile surfaces during their use is a consequence of various stresses resulting from the influence of external loads. In the adapted method in a laminar hood, small tensile/compressive loads in arbitrary directions as encountered in the conditions of use are covered. In order to bring the method closer to real conditions, in the future, it is planned to upgrade the device with an abrasive element that will simulate frictions in use.

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