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Fibre persistence on static textiles under outdoor conditions

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Abstract

The persistence of fibres under outdoor conditions is seldom investigated. This research aimed to study simultaneously the influence of several factors (and their cross-interactions) on the persistence of fibres on static textile surfaces. In order to achieve this aim, a design of experiments was successfully implemented under laboratory conditions. Four factors were considered: time, inclination of the recipient textile, wind speed, and rainfall. The model obtained by this supervised method was compared with the results collected under actual outdoor conditions near a weather station.

The resulting model appears to be reliable as long as the values of the factors are kept within the range used in the study. The results of the laboratory tests showed that wind speed and rainfall significantly influence the persistence of fibres while time and inclination of the recipient textile have been found to be nonsignificant.

In general, the observed persistence was high: between 90.4 and 100 %. This might be attributed to the recipient textile surface possessing abundant protruding fibres which "traps" the transferred fibres.

Outdoor experiments usually suffer from a higher variability and result in a higher fibre loss. In outdoor conditions, wind and rainfall have shown an extensive influence on the fibre persistence. Finally, the trend of fibre persistence on static textiles in outdoor conditions is generally linear with time, but extreme meteorological condition will induce exponential losses.

Key words: Trace evidence; Textile fibres; Design of experiments (DOE); Wind speed; Rain.

Highlights

- Rain and wind have a significant influence on the persistence of fibres.
- Fibre loss was less predictable in outdoor tests than in laboratory tests.
- Fibre loss on static textiles in outdoor conditions was generally linear with time.
- Extreme meteorological conditions cause exponential fibre losses on static textiles.
- The persistence of transferred fibres on textiles with protruding fibres is high.

1. Introduction

Textile fibres are a very common type of trace evidence as they are present in our everyday lives. In forensic science, fibres are mostly investigated in serious offences like homicide, assaults, kidnapping and rapes. These fibres can be transferred when a contact occurs between different textile items (clothing, furniture, car seat…). The search and recovery of fibres rely heavily on the understanding of how such traces are transferred and persist on different surfaces. The evaluation of fibre persistence will determine if a certain number of fibres are expected to be found given the case circumstances. Thus, the persistence parameter often plays a critical role when pre-assessing fibre evidence in casework and is also a key parameter for evaluative reporting at the activity level.

The number of fibres that will persist on an item is directly dependant on the number of fibres that were initially transferred during the contact. The main parameters influencing this quantity are the donor garment, the recipient and the type of contact (**Schnegg et al.**, 2018b). Concerning the persistence, all of these parameters influencing the transfer remain important but two new parameters become critical: the time elapsed between the alleged contact and the fibre recovery and the activities underwent by the recipient.

In literature, the concept of persistence is often associated to the activity of individuals leaving the crime scene after committing the offence. Typically, police will look for a suspect and forensic evidence will be collected after a couple of hours or days.

Pounds & Smalldon (1975a, 1975b, 1975c) studies are still the go to reference in terms of transfer and persistence of fibres. They carried out several experiments by transferring wool and acrylic fibres on different recipient garments and studied their persistence during wear, during which, they observed an exponential loss of transferred fibres with time. An important concept introduced by Pounds & Smalldon is that not all transferred fibres are equally bound to the recipient material and the state of binding of each individual fibre will drastically affect its persistence. They noted that transferred fibres can either be loosely bound, bound, or strongly bound to the recipient garment. Both loosely bound and bound fibres, which represent 80 % of the transferred fibres, will be lost in the first 4 hours, which explains the high initial loss. Strongly bound fibres represent about 10 % of the transferred fibres and they can persist up to 34 hours. Most authors agree that this exponential loss is what is actually happening in practice for both fibres and hair (**Robertson et al.**, 1982;

Gaudette & Tessarolo, 1987; **Akulova et al**., 2002; **Dachs et al**., 2003; **Boehme et al**.,2009; **Slot et al**., 2017), but there are exceptions to this rule:

- A higher persistence is observed on car seats (**Roux et al**., 2013), on corpses (**Roux & Robertson**, 2013; **Roux et al**., 2013), on clothing deposited in water (**Lepot & Vanden Driessche**, 2015) on stored clothes (**Robertson et al**., 1982), on textile or pig skin in outdoor conditions (**Krauss & Doderer,** 2009a,b; **Palmer & Polwarth**, 2011) or in hair (**Ashcroft et al**., 1988; **Salter & Cook**, 1996; **Palmer & Banks**, 2005).
- On the other hand, fibres are lost more rapidly on shoe soles when walking (**Roux et al**., 1999; **Benett et al**., 2010; **Saunders & Sheridan**, 2018), if the clothes/skin/hair are washed (**Robertson & Olaniyan**, 1986; **Palmer**, 1998; **Palmer & Burch**, 2009; **Szewcow et al.**, 2011; **Hong et al.**, 2014) or if an item is worn on the recipient garment (**Robertson et al.,** 1982).

These differences seem to be mostly linked to the activities relative to the recipient item as fibre loss is reduced on static surfaces and increased when movements or friction are present.

Another aspect of fibre persistence concerns corpses that are found static, but the crime scene is located outdoors and conditions such as rain and wind can induce fibre loss. The literature on fibre persistence in such conditions is sparse.

Krauss & Doderer (2009a) were the only ones to study the persistence of fibre on textiles in outdoor conditions. In this study, 100 cotton, wool and polyester fibres were deposited on different textile surfaces of 12 x 12 cm^2 (cotton, mix polyester-cotton, polyester and acrylic) and placed outdoors for 42 days. They highlighted that the persistence depends on the textile structure with rough surfaces showing a higher persistence than smooth ones. Heavy rain (9 L/m^2) lowered significantly the persistence of fibres. This was not the case for light rains and wind speeds up to 17 m/s. All the fibres were never completely lost, and persistence curves were rather linear with a drop (steeper gradient) when heavy rain occurred.

Krauss & Doderer (2009b) reached similar conclusions with experiments carried out on pig skins of 10 x 10 cm^2 in outdoor conditions for 14 days. Moderate losses were globally observed, except on day 12 when heavy rain (9 L/m^2) was registered. Wind speed of up to 6.7 m/s did not have any significant impact on fibre losses. All the fibres were never completely lost and some of them remained after 14 days.

Palmer & Polwarth (2011) realised new tests on half-pig carcasses over a period of 12 days. Fibres were transferred by actual contacts and not deposited as it was the case in the **Krauss & Doderer** (2009a,b) studies. Most of the fibres were lost in the first 2 days but they never witnessed a complete loss. An exponential loss of fibres was observed, even in the absence of heavy rain and wind, but to a lesser extent than one observed in living subjects. Rain caused major losses, with or without wind, while wind alone had a slight influence on losses.

The effect of water flow may also be indicative when considering the study of persistence in rainy conditions and a couple of studies are available in literature.

Lepot et al. (2015) focused on the persistence of fibres on different garments during an immersion/emersion process in water. Their results show that the persistence values depend on the textile structure: textured garments (cotton T-shirt, fleece and acrylic pullovers) showed persistence values between 80 and 90 % while smooth garments (polyester) only have persistence values of around 20 %. According to the authors: "the amount of protruding fibres and the density of the rough fibrous network at the surface of the recipient garment are both key factors that increase the persistence value". The influence of the recipient textile structure (protruding fibres and rough fibrous network) was also observed by **Boehme et al.** (2009) in their persistence experiments of animal hairs on textiles.

Lepot & Vanden Driessche (2015) studied the persistence of fibres on cotton T-shirts immersed in running water. Under laboratory conditions, a gentle water flow (0.4 L/s) only slightly affected the fibre persistence which remained almost constant over time. Most fibres were lost during the immersion and emersion processes. Under real conditions, including a medium water flow (2000 L/s) and boat activity, the immersion/emersion steps also caused the majority of fibre losses. Following the immersion, a slow and linear decreasing persistence curve was observed over time: about 1.5 % loss per hour in medium flow running water.

Considering the persistence of fibres after the utilization of a machine washing, several authors (**Robertson & Olaniyan**, 1986; **Palmer**, 1998; **Szewcow et al.**, 2011) observed a redistribution of fibres on the textile as well as on other textiles that were washed together. The global persistence after washing is low (about 1 to 15 %) and related to the persistence properties of the fabrics. **Palmer & Burch** (2009) observed a complete loss of fibres on the skin of living individuals after a shower or a bath. The persistence of fibres on hands of living individuals after washing was studied by **Hong et al.** (2014): between 3 and 5 % persisted 10 minutes after a 10 seconds hand washing, these fibres were mostly located in fold of skin or in hairs suggesting that the skin texture has an influence on the persistence.

Overall, the exponential persistence curves with a high initial loss during the first 4 hours seem to correspond to the majority of the situations. Persistence seems to be also highly dependent of the recipient surface texture. On the other hand, linear persistence curves are sometimes observed on car seats, static surfaces exposed to outdoor conditions or immersed in water.

This work aimed to study the persistence of fibres exposed to outdoor conditions in order to aid experts in the evaluation of this type of trace material on clothed static corpses found outside. At the moment, only a limited amount of published articles can be found (**Krauss and Doderer**, 2009a,b; **Palmer & Polwarth**, 2011). In these researches, the effect of the factors and their interactions were not studied simultaneously. **Krauss and Doderer (**2009a,b) concluded that if all of these studies show a high fibre persistence (up to 12 to 42 days), rain had more influence than wind on persistence and such surfaces have rather linear persistence curves. On the other hand, **Palmer & Polwarth** (2011) found an influence of both rain and wind and also observed exponential persistence curves.

This research studies simultaneously the influence of several factors (and their cross-interactions) on the fibre persistence on static textile surfaces. In order to achieve this goal, a design of experiments was successfully implemented under laboratory conditions. Four factors were considered: time, inclination of the recipient textile, wind speed, and rainfall. The model obtained by this supervised method was compared with the results collected on static textiles under actual outdoor conditions near a weather station.

2. Material and Methods

Two sets of experiments were conducted: the first one in the laboratory using a design of experiments (DOE) and the second one under outdoor conditions near a weather station.

2.1. Methodology

In order to facilitate the counting of transferred fibres, a UV fluorescent pink pullover was chosen as the donor garment (warm hood, Coral, Kalenji, from Decathlon, France). Its composition is 91 % polyester and 9 % elastane, but only the polyester fibres were transferred. The recipients were black T-shirts that were 100 % cotton (M-Budget from Migros, Switzerland). Cotton was chosen as it is highly common. Recipient textiles were cut and fixed onto a wooden square backing of 15 x 15 cm^2.

Transfers were carried out in the following way: the donor garment was laid over the recipient garment fixed on the wooden square. Homogeneous pressure was applied between both textiles using another wooden square of the same size (15 x 15 cm, 440 g). The donor garment was then slightly rubbed twice on the recipient. The amount of transferred fibres was then checked under UV illumination. This number was ensured to be between 100 and 500 fibres in order to facilitate the visualisation and the counting of transferred fibres. If the transfer was not within the specified range, a new transfer was performed. The same donor garment was used, and the recipient textiles were reused after decontamination.

Before each transfer, the recipient textile was cleaned using adhesive tapes and the absence of fluorescent fibres was ensured. After the transfer, the recipient textiles were moved either to the laboratory or to the deposition site outdoors and fixed in place. For the outdoor tests, special transport boxes were used in order to protect the samples. The fibre losses during these manipulations were first evaluated in the following way. A first photograph was taken directly after the transfer, and a second one after the transport and manipulations. These tests were realised 3 times indoor and outdoor. For the laboratory handling, no fibre losses were observed twice and a loss of 1.9 % was observed once (4 fibres out of 214). For the outdoor handling, no fibre loss was observed twice and a loss of 0.2 % once (only 1 fibre out of 639 was lost). These losses during the sample manipulations were thus considered negligible.

2.2. Fibre counting

Transferred fibres were counted directly after the transfer (T_0) and then subsequently after the expositions of the recipient garment to different conditions. Photographs of the recipient textile square placed in a wooden static support were taken in standardised conditions using a Canon Eos 6D (Canon Inc., Tokyo, Japan) camera equipped with an EF 50 mm f/2.5 Compact Macro objective and an orange observation filter (Rodenstock Orange 22 58 mm, 12-1095-320-005-80). Two Polilight® PL500 (Rofin Pty Ltd, Melbourne, Australia) were used to illuminate the sample uniformly at a wavelength of 350 nm. A diagram of the experimental setting can be found in section 2.5.

These photographs were taken in a different room than the one used for the transfer to avoid contamination. A photograph under visible light was also taken as a reference. Photographs taken in CR2 format were first converted in DNG (DNG Converter, version 9.7.0.668, Adobe, California, USA). A semi-automated method for fibre counting was developed using Camera Raw (version 10.5, Adobe, California, USA) and Photoshop CC 2015 (version 2015.16.0, Adobe, California, USA) (see Figure 1a). First, some adjustments by a developed script were carried out using Camera Raw in order to maximise the contrast of the fibres and to obtain a homogeneous black background (see Figure 1b). Second, the black background was selected using the "Colour Range" command in Photoshop, and then this selection is reversed so that only the fibres were selected (see Figure 1c). This two-step selection allows for a better selection of the fibres, because the black background is homogeneous while the colour of the different fibres is subject to variation. This selection, although very satisfactory and precise in general, is, however, subject to some error. It was therefore necessary to check every selection briefly. Thus, a grid was added to facilitate the counting and the visual verification of each selection to avoid errors (see Figure 1c). For example, two fibres could be selected in the same zone and counted as one (most frequent error). The number and location of these zones were then recorded as measurement logs and a Photoshop layer was created. This layer was then used as a reference to visually count missing fibres after the persistence experiments on the same recipient textile.

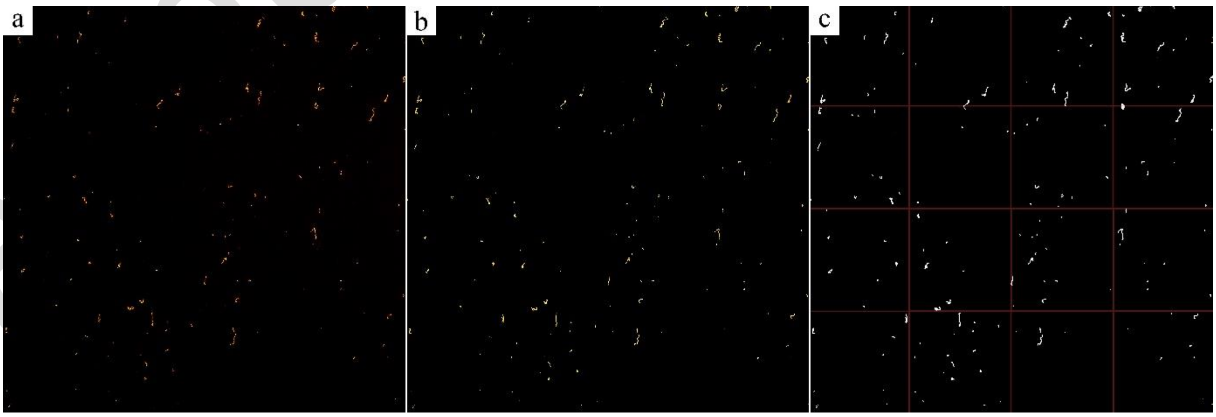

Figure 1. *Different steps of images treatment: original image (a), image after the adjustments in Camera Raw (b) and image after contrast inversion with the red grid (c).*

2.3. Selection of influent factors

Three common factors were considered in the literature concerning the persistence of fibres in outdoor conditions (**Krauss & Doderer**, 2009a, b; **Palmer & Polwarth**, 2011): the speed of wind, the force of impacting rain and the time elapsed between the transfer and the recovery of fibres. In this research, these three factors were considered, in addition to the inclination of the recipient textile.

The recipient textile surface structure is also often mentioned as an important factor influencing the fibre persistence (**Krauss & Doderer**, 2009a; **Lepot et al.** 2015), however the choice here was to limit the study to solely the external factors mentioned. Another practical difficulty was to find textiles with measurable surface roughness while keeping all the other parameters identical (i.e. composition, textile structure…). Such a sample set was not available.

2.4. Laboratory tests

To simulate outdoor conditions, a specific assembly was constructed: two wooden squares equipped with the recipient textile were held with metallic bars and oriented at the chosen angle over a sink. An electric tower fan (Primotecq Skyline from Fust SA, Switzerland) was used to simulate the wind and a water delivery system made up of two garden sprinklers (City Gardening Kit from Gardena AG, Germany) connected to the tap was used to mimic rainfall (see Figure 2 in the next section).

2.5. Experimental designs, indoor tests

Unscrambler® X 10.1 software (CAMO Software AS., Oslo, Norway, 2009) was used to create and analyse the design of experiments (DOE). The selected response is the fibre losses expressed in percentage [%]. A face-centred central composite design (FCCD), was chosen. This choice was based on the literature review which showed that FCCD is the method of choice when the selected factors have an influence on the response (i.e. the persistence of fibres). Several models of increasing complexity (linear, linear with 2nd order interactions and quadratic) were tested with and without some of the factors. The best and simplest significant model for response surfaces was validated and chosen by analysis of variance (ANOVA) and minimising the p-values of the regression significance F-tests and at the same time by maximising the p-value of the lack-of-fit F-tests. A significance level at 95 % confidence level was considered, so the significance or the risk level (α) was equal to 0.05. Hence, if the p-value is ≥ 0.05, it is considered non-significant, within the range [0.01:0.05] weakly significant, within the range [0.005:0.01] moderately significant and < 0.005 highly significant. The impact on the response of each factor in the validated and chosen model was determined by the analysis of the response surfaces which stem from the second order polynomial model including the main factors, their two-factor interactions and the quadratic terms, obtained by the least square methodology. Each experiment was randomly performed once and six centre points were measured to assess the model validity (**Box et al.**, 2005; **Goupy**, 2013; **Ferreira et al**., 2007), for a total of 30 experiments. The variance homogeneity was presupposed on the experimental range (homoscedasticity).

Factors selected for this study are the time elapsed between the transfer and the recovery of fibres (A), the inclination of the recipient textile (B), the wind velocity (C) and the force of impacting rain (D). For each of the chosen factors, three evenly distributed levels are needed. The range of variability for each factor is defined between a low level (-1) and a high level (+1), with level 0 representing the centre value. The time factor (A) was limited to working hours: the high level (+1) was set for 8 hours, the low level to 2 hours and level 0 corresponds to 5 hours. The inclination factor (B) varies from horizontal (low level, 0 ° degree) to vertical (high level, 90 ° degrees, +1) with a centre value of 45 ° degrees. The speed of wind (C) was measured 7 times every 15 minutes using a rotating vane anemometer 417 (Testo AG, Lenzkirch, Germany) fixed at the position of the textile samples. This was done for the 8 different settings of the electric tower fan. The low level (-1) was fixed as an absence of wind (0 m/s), the high level (+1) at 1.6 m/s (setting 7 of the fan) and the centre value at 0.9 m/s (setting 4 of the fan). The standard deviation was lower than the precision of the instrument (0.1 m/s). These wind values are rather low as they correspond to small wavelets on water with no plant movement for the 0.9 m/s and wavelets on water and small vibration of the plants for the 1.6 m/s. However, these values were also observed in other studies (**Palmer & Polwarth**, 2011) and correspond to the mean value measured in outdoor conditions over the five outdoor tests during this work.

For the rain (D), it was necessary to calibrate the positions of the water tap. The rain was measured using a logging rain gauge Pluvimate (Driptych, www.driptych.com) placed vertically in the laboratory sink. The low level (-1) was fixed as an absence of rain (0 mm/h) and the high level (+ 1) was set with the tap almost fully open (100 ± 6 mm/h). The centre value is 54 ± 10 mm/h (level 0). Note that the centre value has a higher variability that the +1 level (water tap fully open). Measures were carried out for a period of 8 and 15 hours to check the water flow stability. The chosen levels correspond to heavy rain, but it was impossible to lower these values as it compromised the spraying process (constant water flow with no droplets).

The selected factors and their levels are illustrated in Figure 2. It is important to note that the centre values (level 0) of the speed of wind (C) and the rain (D) could not be set precisely in the middle of the experimental range. Figure 2 represents a sketch of the experimental settings.

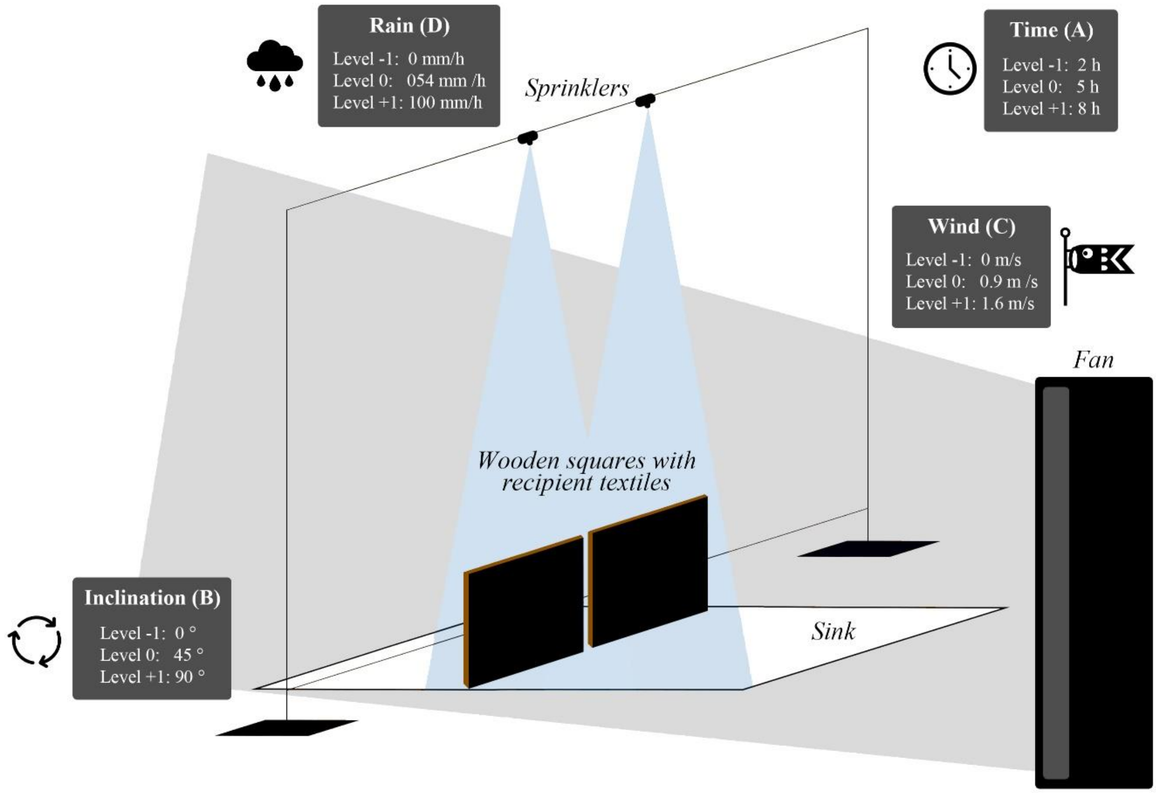

Figure 2. *Sketch of the experimental settings for indoor experiments, the 4 selected factors A, B, C and D and their 3 respective levels.*

2.6. Outdoor tests

Outdoor tests were also carried out during a 3 to 4 days period over five different weeks that had different weather conditions (outdoor tests n° 1 to 5). Textile samples were prepared in the same way as for the laboratory experiments. The wooden square with the recipient textiles were fixed on a laboratory stands. They were then deposited 30 m from the Swiss Federal Institute of Technology's (EPFL) weather station in a semi secured area. Their axis was always in the same orientation. During the first two outdoor tests, only one horizontal textile sample was deposited and in the next three outdoor tests, textile samples at 0, 45 and 90 degrees were tested simultaneously. Every 24 hours, over a period of 3 or 4 days, the samples were removed and photographed using the same procedure as previously described. They were then replaced at the same position.

3. Results and discussion

3.1. Laboratory tests

3.1.1. Experimental design

The sequence of experiments and the levels of the four factors (time, inclination, wind and rain) were created using the Unscrambler software. The fibre losses measured for each of the 30 experiments can be found in the appendix, Table A1. These losses were counted together on both textile squares hold with the same metallic bars in order to combine the wind and rain variabilities that could be induced by the position of the textile in the laboratory experiments.

The validated and chosen model considering response surfaces (see Section 2.5 for details) had a very low p-value of 0.0004 for regression significance and at the same time a very high p-value of 0.9484 for the lack-of-fit. This model was considered highly significant and trusted to describe the response surfaces adequately, hence it could be adequately used to model and to interpret the percentage of fibre losses. The linear (p-value = 0.0013), two-way interactions between two variables (p-value = 0.0058) and quadratic parts (p-value = 0.0072) of the model were highly and moderately significant respectively (see section 2.5 for terminology), which showed that they were useful for the conception of models.

The final model contains only the factors wind (C) and rain (D), their two-way interactions and their quadratic terms part. The significance of their effects on the fibre losses are presented in Table 1.

Effects	**Percentage of fibre losses**	
	Significance (p-value)	***Effect value***
Wind (C)	Highly non-significant	0.0960
Rain (D)	Highly positive	1.9046
Wind * Rain (CD)	Moderately negative	-1.4529
Wind * Wind (CC)	Weakly positive	2.3573
Rain * Rain (DD)	Weakly negative	-2.7311

Table 1. *Analysis of significance of the effects on the fibre losses applying an FCCD experimental design (see section 2.5 for terminology).*

It interesting to note that the time (A) had no influence on the model (p-value = 0.8851[1]). But, as already mentioned by **Roux et al.** (1999), the time itself is important only because it gives the opportunity for activities to happen: in their research concerning fibres on shoe soles, it was the activity of walking which resulted in the losses. Similarly, in the present survey the occurrence of wind and/or rain on our static textile samples is the activity in question rather than the time elapsed. It was also suggested that the accumulation of events is more important than their duration over time. Returning to the present study, the inclination (B) also shows no influence on the fibre losses (p-value = 0.9859[1]). This result may be influenced by the surface textile structure used (see Section 3.1.2).

[1] This p-value is obtained with the model including the following effects: Time (A), Inclination (B), Wind (C), Rain (D), Wind * Rain (CD), Wind * Wind (CC) and Rain * Rain (DD).

The FCCD results and the surface response plots indicated that the rain (D) is the major factor influencing the fibres losses and the wind (C) had less influence than the rain, as shown in Figure 3. This corresponds to the results obtained by **Krauss & Doderer** (2009a,b) under outdoor conditions. However, it is important to take into account that the chosen range for wind speed was rather low and the range for rainfall was high. This probably had an impact on the overall results. The fixed orientation of the wind in the laboratory set-up might also explain this low influence on the fibre losses: for the horizontal position (0 °) the wind was parallel to the surface with a negligible impact, for the vertical position (90 °), the wind reached the surface perpendicularly and could tend to push the fibres into the textile surface structure, the same effect was probably also present at the 45 ° position. The interaction between wind and rain also had a combined impact on the fibre losses. The surface responses indicated that the interaction between these two factors caused a decrease in fibre losses as compared to rain only. This might be again explained by the laboratory conditions. The range of the wind speed was too low to have any real impact on the fibre losses, but it might be sufficient to reduce the amount of water and its force of impact on the recipient textile (i.e. lowering the shower effect of the rain), thus decreasing the fibre losses. Another potential explanation for this phenomenon could be the hydrophilic/hydrophobic properties of the fibres. The cotton recipient textile is hydrophilic; thus, it attracts and adsorbs water which causes its structure to swell. Polyester fibres from the pullover are on the other hand hydrophobic and will tend to move away from the surface of the wet recipient textile, repelled by water. This could explain the greater fibre losses when there is no wind. With the addition of wind, the surface of the recipient textile tends to dry and thus decrease the hydrophilic/hydrophobic interactions between the fibres. None of these potential explanations was further tested in the present study but could be investigated in the future.

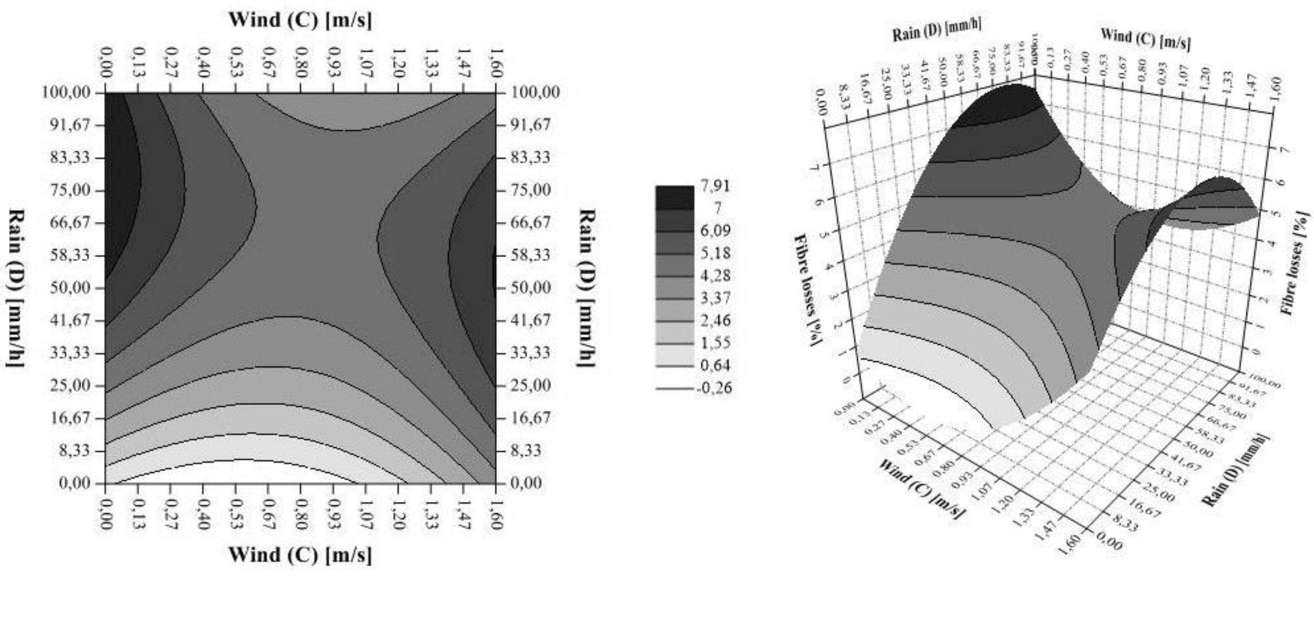

Figure 3. *Surface response plots for the model of the relation between rain and wind. The darker the surface, the higher the response.*

3.1.2. General considerations and influence of the textile surface structure

A more general observation is that the fibre losses between 2 and 8 hours are limited between values of 0.0 to 9.6% (see Appendix, Table A1). These values do not correspond to the **Pounds & Smalldon** (1975b,c) model, which showed around 80% losses in the first 4 hours. These values correspond more closely to the ones obtained by **Lepot & Vanden Driessche** (2015) for the persistence of fibre on cotton T-shirts immersed in running water with about 1.5% loss per hour in medium flow, or to the values obtained by **Krauss & Doderer** (2009a,b) on the persistence of fibre on textiles or pig skin in outdoor conditions. As noted by **Lepot et al.** (2015), cotton T-shirts are textured garments that showed high persistence values following an immersion/emersion process (between 80 and 90%).

Following these observations, more consideration was given to the chosen textile and its surface structure in order to understand this high fibre retention. Observations using a stereo microscope M125 (Leica Microsystems GmbH, Wetzlar, Germany) show protruding fibres on the surface of the new recipient garment. The amount of protruding fibres increased with the use of adhesive tape (see Figure 4), as was done before and between all the experiments. As already mentioned in the literature, protruding fibres is described as a factor increasing fibre and hair retention (**Dachs et al**., 2003; **Boehme et al**., 2009; **Lepot et al**., 2015).

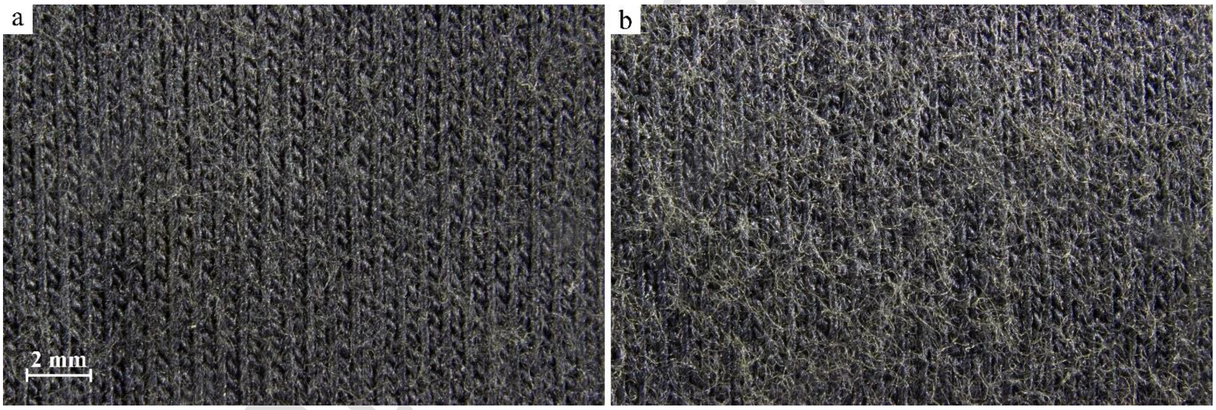

Figure 4. *Surface of the new recipient textile (a) and as used in the experiments after the decontamination of its surface using adhesive tape (b). Note the increase of protruding fibres on the used textile surface.*

This surface degradation of the recipient textile might have induced a drift in the form of a gradual smaller variance in experiments, which could have impacted the results (**Box et al**, 2005; **Goupy**, 2013). In order to evaluate this drift, the results obtained for the 6 central points were considered and plotted according to the ranking of the experiences using the Excel software (version 16.24, Microsoft, USA), as illustrated in Figure 5. A slight diminution of the fibre losses with the ranking of the experiences was observed.

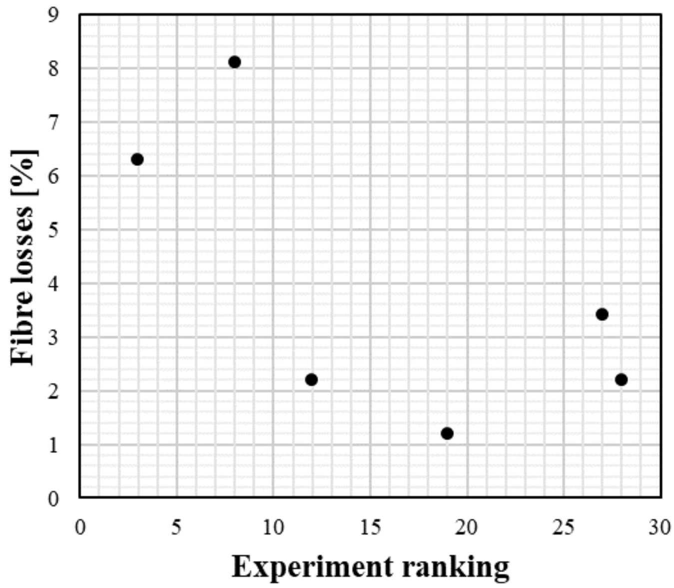

Figure 5. *Fibre losses in percentage according to the experiment ranking for the central points (Time (A) = 5 h; Inclination (B) = 45 °; Wind (C) = 0.9 m/s; Rain (D) = 54 mm/h).*

Figure 5 confirms the observation that protruding fibres slightly increase the fibre retention. However, it was not possible to correct for this drift as the recipient textiles were used at random and the degree of wear could not be objectively evaluated. More work needs to be done on textile surface structures, but this was out of the scope of this project.

It was also observed, as mentioned in the literature, that most of the transferred fibres did not move significantly on the recipient surface. This phenomenon was specifically studied with a new transfer and persistence test under the following conditions: time: 2 h, inclination: 0 °, wind: 0 m/s, rain: 100 mm/h. Ten fibres were randomly chosen, their locations registered, and photographed at t_0. After the test, the recipient textile was dried in a protected location overnight and new photographs were taken. Results for seven representative fibres are illustrated in Figure 6: only one fibre was lost as the seven others slightly changed their orientations but remained almost at the same location. One explanation for this result could be that the number of anchor points determines whether a fibre remains on the textile or is lost. The higher the number of anchor points, the more strongly the fibre is retained by the recipient textile and is more likely to remain there. The initial number of anchor points of fibres is unknown, but it depends, among other things, on the initial contact between the textiles (duration, strength and friction). It has to be noted that the chosen fibres selected in these few experiments are rather long (> 4 mm) but the global persistence in the whole survey is high also for all the shorter fibres as illustrated in Figure 1.

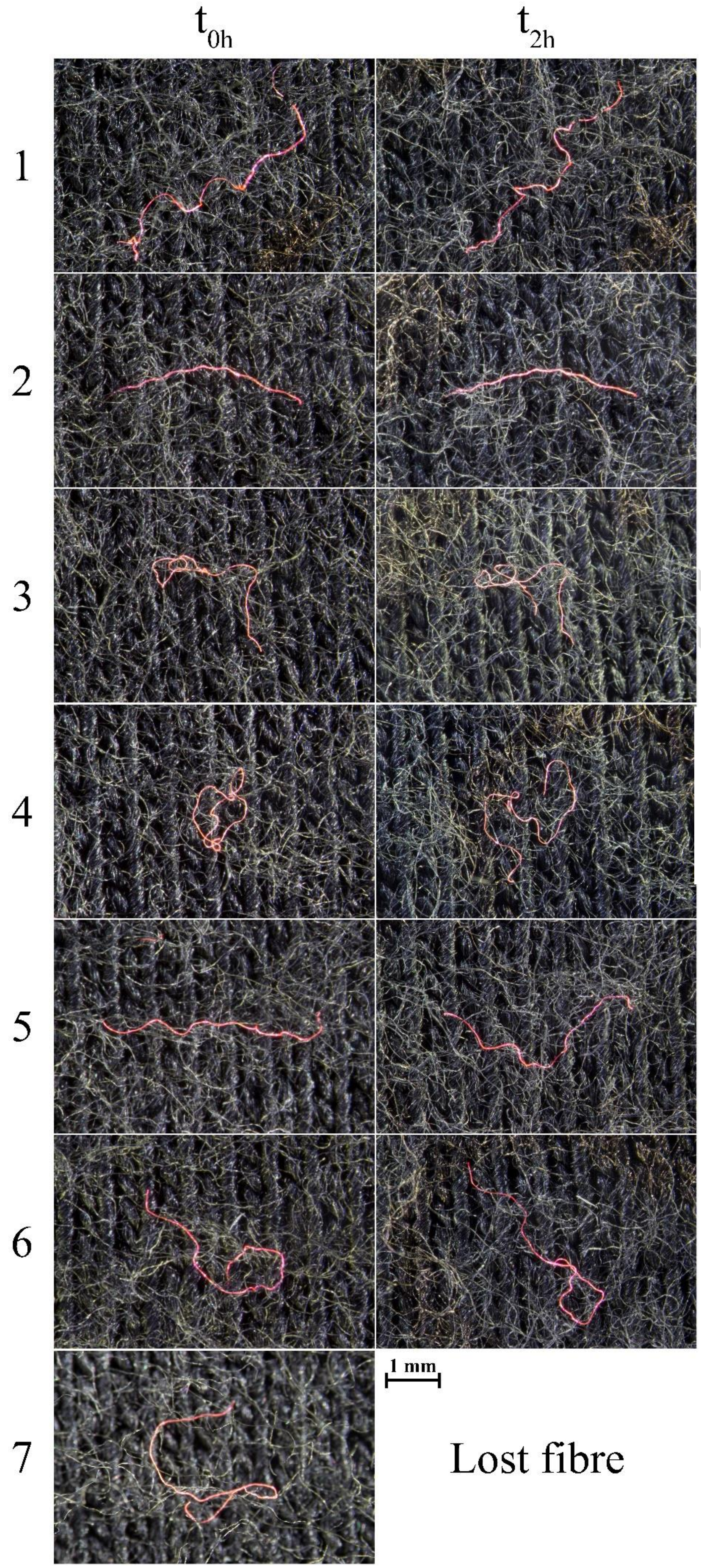

Figure 6. *Seven fibre positions at t_0 and after 2 hours, exposed to windless rain (100 mm/h), horizontal recipient textile position.*

Overall, all these observations confirm that the recipient textiles, and particularly their surface textures, are a preponderant factor that influences the persistence of fibres. This is especially the case for cotton textiles which present protruding fibres on their surfaces (**Dachs et al**., 2003; **Boehme et al**., 2009; **Lepot et al**., 2015). **Boehme et al.** (2009) also made the assumption that textiles with lint shows a higher persistence. It was also observed, towards the end of the experiments, that lint was formed on the recipient textile supporting the assumption of a higher persistence in the presence of lint.

Finally, it was also noticed that with the simulated rain, a layer of water was present at the surface of the recipient textile. This layer of water seems to push the fibre into the textile structure instead of washing them away. It is not known if this layer of water will appear on all types of textile, but it is probably enhanced by the presence of the wooden square placed behind the textile.

3.2. Outdoor tests

These outdoor tests were carried out over a 3 to 4 days period over five different weeks that had different weather conditions. For outdoor tests n° 1 and 2, only the 0 º inclination of the recipient textile was tested and for outdoor tests n° 3 to 5 all of the inclinations were tested. The weather station was located 30 m away from the test deposition site. Wind and rain values were recorded for each day including their maxima and mean values. The fibre losses measured for the five outdoor tests can be found in the appendix, Table A2. The relative orientation of the wind compared to the orientation of the textile recipients was also considered. However, no relationship was found between these relative orientations and the observed fibre losses over the five outdoor tests period.

3.2.1. Outdoor tests, wind and no rain

For outdoor tests n° 1 to 3, no rain was recorded. The fibre persistence was noted every day, as well as the wind speed with maximum and mean values. The results are shown in Figure 7.

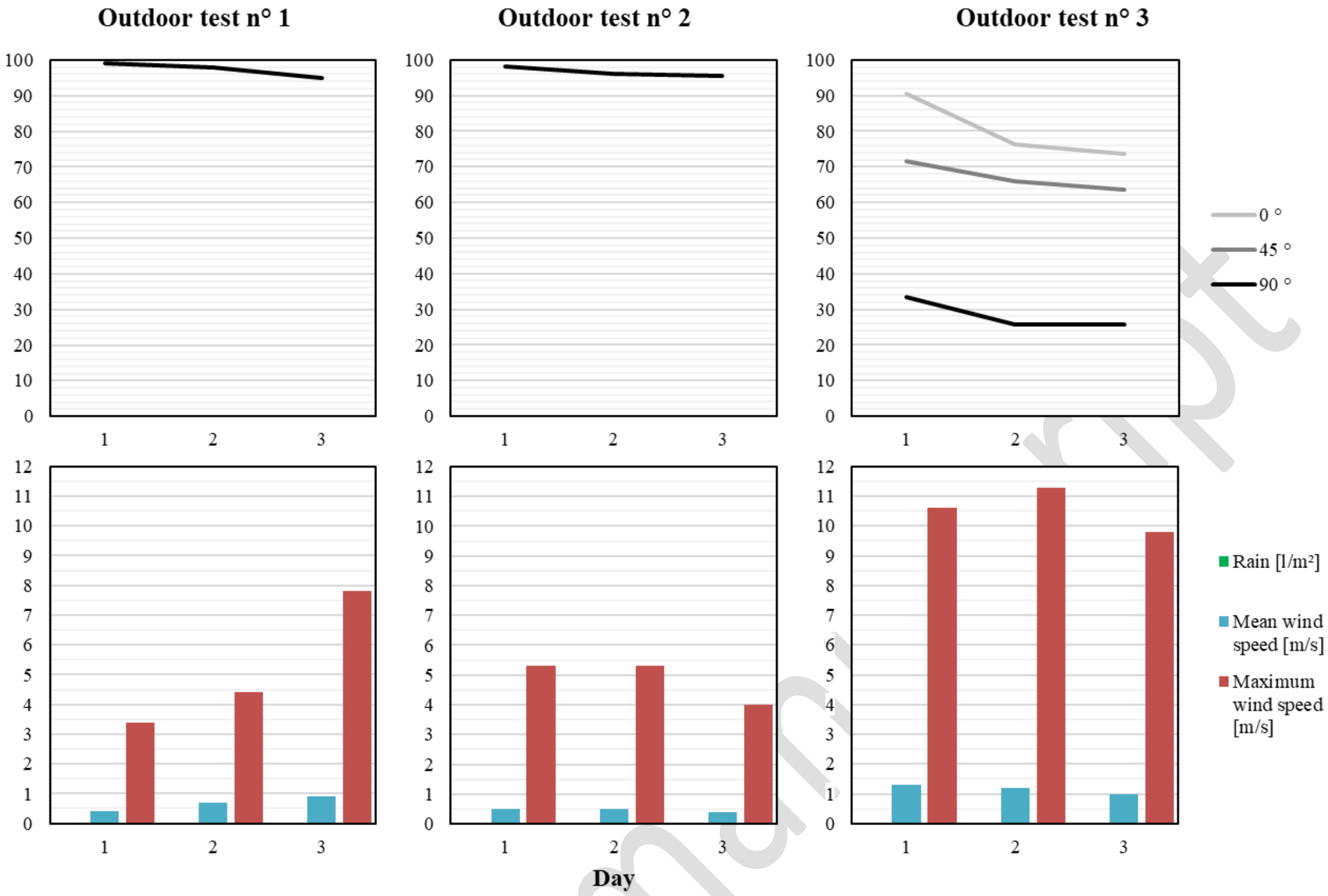

Figure 7. *Fibres persistence % (curve plots) with the wind in the absence of rain, outdoor tests n° 1 to 3. The recipient textile was horizontal (0 °) for outdoor tests n° 1 and 2, and with different inclinations for outdoor test n° 3 (0 °, 45 °, 90 °). The mean and maximum wind speed is respectively the blue and red bar plots.*

For outdoor tests n° 1 and 2, the maximum wind speed was 7.8 m/s and 5.3 m/s respectively. The persistence curves are rather linear with fibre losses between 5.1 % and 4.4 % over a 3 day period (72 hours). For these outdoor tests, the greater the maximum wind speed, the greater the fibre losses are over a one-day period. These results show an influence of the wind on the persistence of fibres and is consistent with the laboratory tests. These losses are low and the results correspond to the ones obtained by **Krauss & Doderer** (2009a, b) under outdoor conditions in the absence of rain.

For outdoor test n° 3, the maximum wind speed was higher, between 9.8 and 11.3 m/s over the 3 day period. Under these circumstances, the persistence curves become more exponential, with a higher loss on the first day (21.3 to 61%), especially with an inclination of 45 ° or 90 ° degrees. An influence of the recipient textile inclination was observed: fibre losses are the highest at 90° and the lowest at 0°, after 3 days, 74% of fibres were lost on the vertical textile recipient, 34% with an inclination of 45° and only 24% on the horizontal textile. These outcomes show the influence of both the wind and the inclination on fibre persistence. These results correspond more to the one obtained by **Palmer & Polwarth** (2011), with an exponential loss in the absence of rain. In their study, the maximum wind speed, for their first

3 days, was between 3.8 and 8.2 m/s with an absence of rain. Around 75-80% of acrylic and wool fibres were lost on pig carcasses. In this survey, the persistence is generally higher than the one from **Palmer & Polwarth** (2011). If the inclination of the textile plays a role, the specific textile surface structure of the T-shirt used here, with high retention properties, potentially explains the difference.

3.2.2. Outdoor tests, wind and rain

For outdoor tests n° 4 and 5, both wind and rain were encountered. The persistence results are presented in Figure 8 for outdoor test n° 4 and in Figure 9 for outdoor test n° 5.

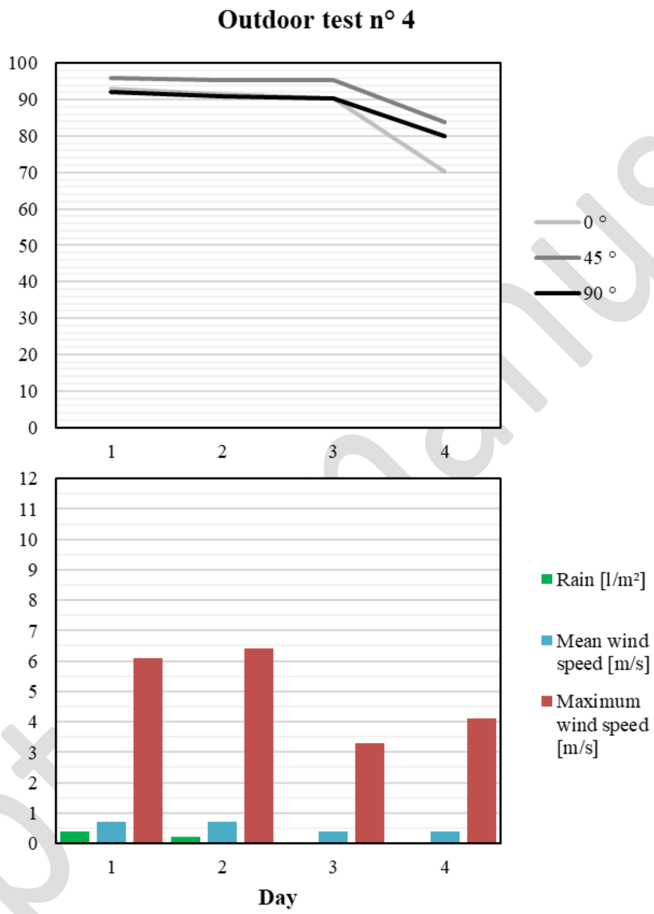

Figure 8. *Fibres persistence (curve plots) for outdoor test n° 4 with rain (green bar plots). The mean and maximum wind speed is respectively the blue and red bar plots. The recipient textile was in different inclinations (0 °, 45 °, 90 °).*

For outdoor test n° 4, the fibre losses vary with the inclination between 4.6 and 9.8 %. For the first 3 days, with the combination of rain and wind, the persistence curve is rather linear. These values are a little higher than the one obtained for outdoor tests n° 1 and 2 where only wind was present (between 4.4 and 5.1 %). The inclination had a moderate impact with a higher retention at 45 °. On day 4, there is an important and unexpected drop of fibres in the absence of rain and with a wind maximum speed of only 4.1 m/s. These fibre losses cannot be explained by meteorological conditions. The only other hypothesis for this loss is from unknown activity, human or animal. However, as this site was not under any surveillance, this could not be corroborated or invalidated.

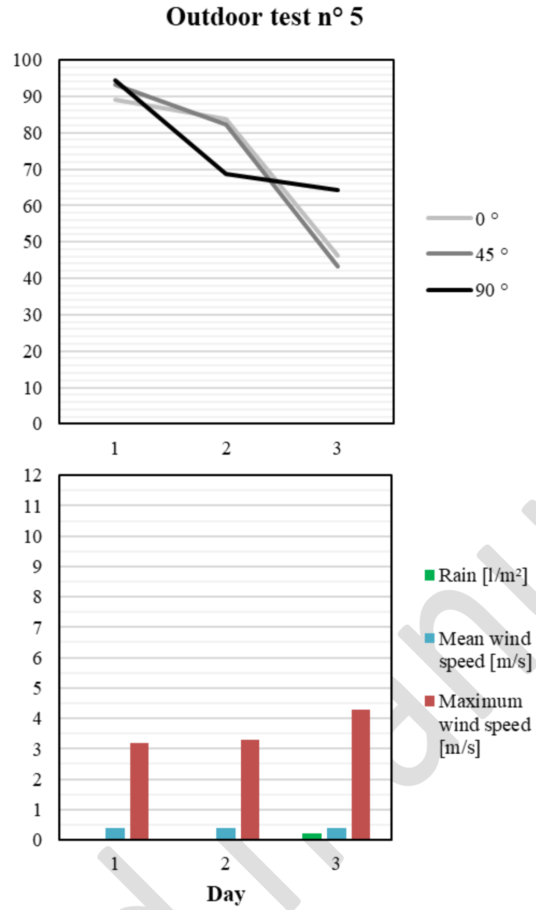

Figure 9. *Fibres persistence (curve plots) for the outdoor test n° 5 with rain (green bar plots). The mean and maximum wind speed is respectively the blue and red bar plots. The recipient textile was in different inclinations (0 °, 45 °, 90 °).*

For outdoor test n° 5, linear losses were observed for days 1 and 2 in the absence of rain and with a maximum wind speed between 3.2 and 3.3 m/s, with an exception for the vertical recipient (90 °) for which an important loss was observed on day 2. These losses between 5.6 and 27.2 % are in general higher than the ones obtained for the first two days of outdoor tests n° 1 and 2 (between 2.1 and 3.8 %) where the wind was a little stronger. The reasons for these higher losses cannot be explained by meteorological conditions, but, as with for outdoor test n° 4, the activities around the recipient textile were not known and could have had an impact. On day 3, the occurrence of light rain (0.2 mm/h) increased the fibre losses considerably. For outdoor test n° 5, these almost linear persistence curves in the absence of rain accompanied with a significant dip when the rain is present correspond to the observations of **Krauss & Doderer** (2009a, b) under outdoor conditions.

Overall, it is interesting to note that the inclination of the recipient textile (B) that was not significant in the fibre losses in the laboratory tests becomes a significant factor with high wind speeds during the outdoor experiments. This observation tends to support the notion that there is a significant interaction between these two factors, even if more data is needed before a general conclusion can be drawn for this parameter.

3.2.3. Outdoor tests, model prediction

The constructed laboratory model based on the experimental design was used as an attempt to predict the fibre losses in the meteorological conditions encountered outdoors. For these predictions, the mean values for wind (C) and rain (D) were used. The results show that the observed fibre losses were generally higher than the ones predicted by the constructed laboratory model, even if the mean values for wind (C) and rain (D) are in accordance with the experimental range of the laboratory values. These results indicate that the maximum values for both wind and rain are probably the ones that would need to be used in the model to predict the fibre losses in the meteorological conditions encountered outdoors. Unfortunately, predictions using the maximum wind values are impossible with this model as extrapolations can only be done for values included in the experimental range, which is not the case here. Thus, these results show that the wind speeds tested in the laboratory were much too low to obtain a statistical model applicable outdoors.

4. Conclusion

The aim of this research was to understand the factors influencing fibre persistence on static textiles under outdoor conditions, as it would be the case for clothed corpses deposited outside.

Laboratory experiments under controlled conditions were carried out considering four influencing factors: the time (A), the inclination of the recipient textile (B), the wind speed (C) and the rain (D). Thirty experiments were carried out using a design of experiments.

Rain (D) was found to be the most influent factor with wind (C) also having an influence as well as the interaction between these two factors. These results were probably affected by the choice of the ranges as these were high for rain (between 0 and 100 mm/h) and low for wind (between 0 and 2 m/s).

The established model also highlighted that both the time (A) and inclination (B) had no influence on the fibre losses. This shows that the time itself is important only because it gives opportunity for activities to happen, in this case, the exposure of the static textile to wind and rain. It is suggested that the accumulation of events is more important than the duration over time. For the inclination (B), this result may be influenced by the surface textile structure used.

The overall persistence value obtained from laboratory experiments was high: between 90.4 and 100%. This could be attributed to the recipient textile surface (cotton T-shirt), showing a high number of protruding fibres which "trap" the transferred fibres. Most of the transferred fibres only changed slightly in their orientation but did not move from their initial transfer locations. Further research should be carried out specifically taking into account the textile surface structure in order to understand more fundamental principles concerning fibre persistence.

The fibre persistence values observed in outdoor conditions were less predictable. With medium wind conditions, a slow linear decrease was observed, while higher wind conditions turned the persistence curves into an exponential decay. When both wind and rain were encountered at the same time, the results were even less predictable: clearly, more tests under outdoor conditions need to be carried out under video surveillance in order to account for additional external factors (for example, human or animal intervention). Finally, the inclination of the recipient textile seems to have some impact under outdoor conditions.

The calculated fibre losses based on the model predictions were in general inferior to the effective values in outdoor conditions. The main limiting factor was the experimental range of the laboratory experiments which did not fit with the outdoor conditions. In the model, the mean outdoor values for the wind speed were used as they corresponded to the ones chosen in the laboratory experiments. These preliminary results indicated that the maximum wind speed values should be used instead, in order to better predict the impact of sudden heavy wind (as well as sudden heavy rain) on fibre persistence.

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Bibliography

Akulova V, Vasiliauskiene D & Talaliene D. (2002). Further Insights into the persistence of transferred fibres on outdoor clothes. *Science & Justice,* 42(3): 165-171.

Ashcroft CM, Evans S & Tebbett IR. (1988). The persistence of fibres in head hair. *Journal of the Forensic Science Society,* 28(5-6): 289-293.

Benett S, Roux CP, Robertson J. (2010). The significance of fibre transfer and persistence – a case study. *Australian Journal of Forensic Sciences,* 42(3): 221-228.

Boehme A, Brooks E, McNaught I & Robertson J. (2009). The persistence of animal hairs in a forensic context. *Australian Journal of Forensic Sciences,* 41(2): 99-112.

Box GEP, Hunter JS & Hunter WG. (2005). Statistics for experimenters: design, innovation, and discovery. 2nd edition. Hoboken: Wiley Series in Probability and Statistics, Hoboken: Wiley-Interscience.

Dachs J, McNaught IJ & Robertson J (2003). The persistence of human scalp hair on clothing fabrics. *Forensic Science International,* 138(1-3): 27-36.

Ferreira SL, Bruns RE, da Silva EG, Dos Santos WN, Quintella CM, David JM, de Andrade JB, Breitkreitz MC, Jardim IC & Neto BB. (2007). Statistical designs and response surface techniques for the optimization of chromatographic systems. *Journal of Chromatography A,* 1158(2007): 2-14.

Gaudette B & Tessarolo A. (1987). Secondary transfer of human scalp hair, *Journal of Forensic Sciences*, 32(5): 1241-1253

Goupy J. (2013). Introduction aux plans d'expérience avec applications. 5e édition. Paris: Dunod.

Hong S, Han A, Kim S, Son D & Min H. (2014). Transfer of fibres on the hands of living subjects and their persistence during hand washing. *Science & Justice,* 54(6): 451-458.

Krauss W & Doderer U. (2009a). Fiber persistence on garments under open-air conditions. *In:* Trace Evidence Symposium, Clearwater beach, Florida, United States, 2-7 August 2009.

Krauss W & Doderer U. (2009b). Fiber persistence on skin under open-air conditions. *Global Forensic Science Today,* 8: 11-16.

Lepot L, Vanden Driessche T, Lunstroot K, Gason F & De Wael K. (2015). Fibre persistence on immersed garment – Influence of knitted recipient fabrics. *Science & Justice,* 55(4): 248-253.

Lepot L & Vanden Driessche T. (2015). Fibre persistence on immersed garment – Influence of water flow and stay in running water. *Science & Justice,* 55(6): 431-436.

Palmer R. (1998). The retention and recovery of transferred fibers following the washing of recipient clothing. *Journal of Forensic Sciences,* 43(3): 502–504.

Palmer R & Banks M. (2005). The secondary transfer of fibres from head hair. *Science & Justice,* 45(3): 123-128

Palmer R & Burch HJ. (2009). The population, transfer and persistence of fibres on the skin of living subjects. *Science & Justice,* 49(4): 259-264.

Palmer R & Polwarth G. (2011). The persistence of fibres on skin un an outdoor deposition crime scene scenario. *Science & Justice,* 51(4): 187-189.

Pounds CA & Smalldon KW. (1975a). The Transfer of Fibres Between Clothing Materials During Simulated Contacts and their Persistence During Wear – Part I - Fibre Transference. *Journal of the Forensic Science Society,* 15: 17-27.

Pounds CA & Smalldon KW. (1975b). The Transfer of Fibres Between Clothing Materials During Simulated Contacts and their Persistence During Wear – Part II – Fibre Persistence. *Journal of the Forensic Science Society,* 15: 29-37.

Pounds CA & Smalldon KW. (1975c). The transfer of fibres between clothing materials during simulated contacts and their persistence during wear – Part III – A preliminary investigation of the mechanisms involved. *Journal of the Forensic Science Society*, 15: 197-207.

Robertson J, Kidd CBM & Parkinson HMP. (1982). The persistence of textile fibres transferred during simulated contacts. *Journal of the Forensic Science Society*, 22: 353-360.

Robertson J & Olaniyan D. (1986). Effect of garment cleaning on the recovery and redistribution of transferred fibres. *Journal of Forensic Sciences,* 31(1): 73–78.

Roux C & Robertson J. (2013). Interpretation of fiber evidence. *In:* Siegel JA, *Encyclopedia of forensic sciences*, 2nd Edition. Amsterdam: Elsevier, 155-160.

Roux C, Langdon S, Waight D & Robertson J. (1999). The transfer and persistence of automotive carpet fibres on shoe soles. *Science & Justice,* 39(4): 239-251.

Roux C, Robertson J, Palmer R. (2013). Persistence and recovery. *In:* Siegel JA, *Encyclopedia of forensic sciences*, 2nd Edition. Amsterdam: Elsevier, 117-123.

Salter MT & Cook R. (1996). Transfer of fibres to head hair, their persistence and retrieval. *Forensic Science International,* 81(2-3): 211-221.

Saunders R & Sheridan K. (2018). The transfer and persistence of fibres in simulated kicking cases – A pilot study. *In:* ETHG Meeting (European Fibres and Hair Group Meeting), Zurich, Switzerland, 11-15 June 2018.

Schnegg M, Palmer R & Massonnet G. (2018b). Les paramètres clés de l'interprétation des fibres textiles en sciences criminelles. Partie II: transfert, persistance et détection. *Canadian Society of Forensic Science Journal,* 51(3-4): 83-119.

Slot A, van der Weerd J, Roos M, Baiker M, Stoel RD, Zuidberg MC. (2017). Tracers as invisible evidence the transfer and persistence of flock fibres during a car exchange. *Forensic Science International*, 275: 178–186.

Szewcow R, Robertson J, Roux CP. (2011). The influence of front-loading and top-loading washing machines on the persistence, redistribution and secondary transfer of textile fibres during laundering. *Australian Journal of Forensic Sciences,* 43(4): 263-273.

Appendix

Order randomised	Factors				Response
	A: Time [h]	*B: Inclination [°]*	*C: Wind [m/s]*	*D: Rain [mm/h]*	*Fibre losses [%]*
1	2	45	0.9	54	5.8
2	8	45	0.9	54	2.9
3	5	45	0.9	54	6.3
4	5	90	0.9	54	4.1
5	2	0	1.6	100	5.2
6	8	90	0	100	9.6
7	2	0	1.6	0	1.9
8	5	45	0.9	54	8.1
9	8	0	1.6	0	3.2
10	2	0	0	100	8.8
11	5	45	0	54	7.5
12	5	45	0.9	54	2.2
13	5	45	1.6	54	7.3
14	2	90	1.6	100	3.8
15	2	90	0	0	0.3
16	8	0	0	100	5.7
17	8	90	1.6	100	5.3
18	8	0	1.6	100	5.4
19	5	45	0.9	54	1.2
20	5	0	0.9	54	9.1
21	2	90	0	100	6.3
22	5	45	0.9	0	1.7
23	8	90	0	0	1.1
24	8	0	0	0	0.0
25	5	45	0.9	100	3.0
26	8	90	1.6	0	5.2
27	5	45	0.9	54	3.4
28	5	45	0.9	54	2.2
29	2	90	1.6	0	4.4
30	2	0	0	0	0.8

Table A1. *Factor values computed by the DOE for the 30 Random tests carried out in the laboratory and their measured responses in the percentage of fibre losses.*

Outdoor test n°	Day	Mean wind speed [m/s]	Maximum wind speed [m/s]	Rain [l/m^2]	Fibre losses [%]		
					Inclinaison: 0 °	***Inclinaison: 45 °***	***Inclinaison: 90 °***
1	1	0.4	3.4	0	0.9		
	2	0.7	4.4	0	1.2		
	3	0.9	7.8	0	3.0		
2	1	0.5	5.3	0	1.9		
	2	0.5	5.3	0	1.9		
	3	0.4	4.0	0	0.6		
3	1	0.7	6.1	0.4	6.9	4.2	7.9
	2	0.7	6.4	0.2	1.6	0.4	1.2
	3	0.4	3.3	0	1.1	0	0.7
	4	0.4	4.1	0	20.1	11.6	10.3
4	1	0.4	3.2	0	10.9	6.8	5.6
	2	0.4	3.3	0	5.4	10.8	25.7
	3	0.4	4.3	0.2	37.4	39.2	4.5
5	1	1.3	10.6	0	9.5	28.4	66.5
	2	1.2	11.3	0	14.3	5.7	7.8
	3	1.0	9.8	0	2.7	2.3	0

Table A2. *Factor values and fibre losses measured for the five outdoor tests.*