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The Retention of Glass Particles on Woven Fabrics

REFERENCE: Brewster, F., Thorpe, J., Gettinby, G., and Caddy, B., **"The Retention of Glass Particles on Woven Fabrics,"** *Journal of Forensic Sciences*, JFSCA, Vol. 30, No. 3, July 1985, pp. 798-805.

ABSTRACT: It has been demonstrated that the number of particles of glass transferred to fabric is dependent upon fabric type and particle size but that the loss of particles is primarily determined by particle size.

KEYWORDS: criminalistics, glass, fabrics

It was Nelson and Revel [*1*] who first demonstrated the backward ejection of glass particles arising from impact breakage of a glass window. This may be accompanied by transfer of such particles to the clothing and person of the assailant. These workers did not, however, assess the number and size distribution of the particles transferred. Pounds and Smalldon [*2*] carried out a study on the distribution of glass particles on the floor directly in front of a broken window but apart from recording that particles of glass were recovered from the clothing and hair of the assailants nothing was said of the persistence of these glass particles on the clothing. Pearson et al [*3*] reported that 60% of suits submitted to a drycleaners bore at least one glass fragment and the only detailed retention study (Pounds[3]) showed that the persistence of glass on clothing and shoes was dependent on the particle size and the fabric involved. To explore further the position in regard to the persistence of particles on clothing the following detailed study was undertaken.

Experimental Method

Glass

A small pane of window glass, 2 mm thick, was smashed and ground with a mortar and pestle and the mixture sized through a nest of sieves to produce particles in the range 4 to 1mm, 1 mm to 500 μm, 500 to 250 μm, 250 to 125 μm, and 125 to 63 μm which are referred to as sizes 4 mm, 1 mm, 500 μm, and 125 μm, respectively. Samples of 100-mg weight were used for each experiment and the average number of particles per 100 mg was estimated for each particle size by counting the number of particles per 10 mg.

Received for publication 16 Oct. 1984; revised manuscript received 26 Nov. 1984; accepted for publication 28 Nov. 1984.

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[3] C. A. Pounds, "The Efficiency of Searching for Glass on Clothing and the Persistence of Glass on Clothing and Shoes," personal communication, 1977.

Fabric

Two types of fabric were chosen because of their common occurrence and because they represented extremes of texture. These were a wool acrylic mixture (70:30) having a medium to rough texture with numerous surface fibers and washed cotton denim having few surface fibers. Both fabrics were dark blue in color to aid visualization of glass fragments and were used as 30- by 30-cm squares. To aid in particle counting, parallel lines were drawn 2 cm apart across the surface of the fabric squares.

An air rifle (Model BSA.177 Cadet) was used to propel the particles onto the fabric. Preliminary experiments showed the optimum range to be 50 cm for a 30- by 30-cm fabric square. A piece of cotton wool weighing 15 mg was inserted 5 cm from the muzzle of the air rifle before addition of 100 mg of glass particles. For the purpose of firing, the fabric square was attached to the skirt of a shop window model and the rifle discharged perpendicular to this fabric.

Experimental Design

For a particular particle size range the initial number of particles transferred to each of ten woollen and ten cotton denim fabric squares of size 30 by 30 cm was counted with the aid of a long arm microscope using ×20 magnification. Each square was attached to the back of a subject wearing a laboratory coat and pursuing normal laboratory activities. At ½, 1, 2, 4, and 6 h after firing, the squares were removed for examination and the number of particles present counted. This procedure was repeated for each of the 5 particle size ranges, providing 100 data sets on the persistence of glass particles on woollen and denim fabric. On one occasion the same range of glass particles transferred to the woollen fabric was monitored over a five-day period. Mixed samples were also investigated by firing a pre-mixed composition of 50 mg of 125 μm and 50 mg of 1-mm particles onto each of the ten woollen fabric squares.

Mathematical Model

A two-compartment model of the type illustrated in Fig. 1 was proposed to describe the dynamics of glass particles retained on fabric over a period of time. Particles that are in contact with the "surface" compartment S may undergo two possible processes. They may be eliminated from the surface at a rate determined by the rate constant $k_{e\ell}$ or they may become embedded in the "interior" compartment I of the fabric at rate k_{SI}. Particles within the interior compartment may become transferred back to the surface compartment at rate k_{IS}. The penetration, transference, and loss constants can be expected to depend upon the particle size and the type of fabric.

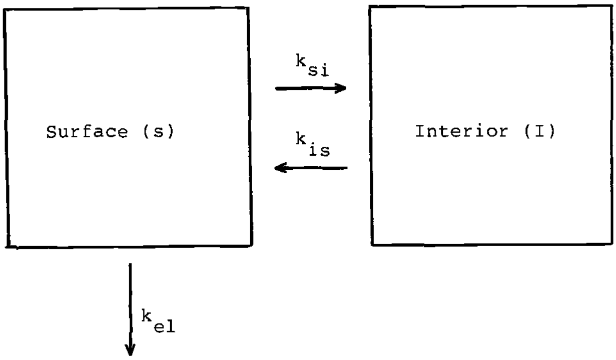

FIG. 1—*Mathematical model for the loss of glass from clothing.*

The process described can be represented by two differential equations for the rate of change of the number of particles in each compartment. These take the form:

$$\frac{dS(t)}{dt} = k_{IS} I(t) - (k_{SI} + k_{e\ell})S(t)$$

$$\frac{dI(t)}{dt} = k_{SI} S(t) - k_{IS} I(t)$$

where $S(t)$ and $I(t)$ denote the number of particles in the surface and interior compartments of the fabric at time t. Simultaneous solution of these equations gives:

$$S(t) = Ae^{\alpha t} + Be^{\beta t}$$

$$I(t) = C(e^{\alpha t} - e^{\beta t})$$

which are the explicit relationships for $S(t)$ and $I(t)$ with time t. A, B, C, α, and β are constants which can be found from the rate constants k_{SI}, k_{IS}, and $k_{e\ell}$. Of particular interest is the equation for $S(t)$, where $A + B$ is the initial number of particles transferred to the fabric and α and β are given by

$$\alpha + \beta = -(k_{SI} + k_{IS} + k_{e\ell})$$

$$\alpha\beta = k_{e\ell} k_{IS}$$

The number of particles observed on fabric at different times should be consistent with the relationship between $S(t)$ and t.

A useful measure of persistence is the half-life $t_{1/2}$ which is the time taken for half the particles to be lost from the fabric. This can be obtained by finding the value of t in the relationship ship

$$S(t) = Ae^{\alpha t} + Be^{\beta t}$$

which corresponds to $S(t)$ equal to $(A + B)/2$. No simple analytic expression exists for $t_{1/2}$ but using the Newton-Raphson [4] iterative method $t_{1/2}$ can be estimated by t_{n+1} after several iterations of the recursive formula:

$$t_{n+1} = t_n - \frac{(Ae^{\alpha t_n} + Be^{\beta t_n} - (A+B)/2)}{A\alpha e^{\alpha t_n} + B\beta e^{\beta t_n}}$$

Computation

For observed values of $S(t)$ at time t the constants A, α, B, and β were estimated using a NAG nonlinear least squares procedure [5] and the half-lives calculated using a BASIC algorithm. All computations were undertaken on a VAX 11/782 mainframe.

Results

Optimum conditions for the firing range were estimated as that distance from the fabric for which visual inspection indicated that the majority of particles were uniformly distributed over the surface of the fabric. Ranges larger than this value resulted in a high percentage of the particles missing the target area while ranges smaller tended to concentrate the particles within a concentric ring on the fabric.

The number of particles fired at the woollen and denim fabrics, the numbers retained, and the loss over the 6-h period subsequent to firing are given in Tables 1 and 2, respectively. Clearly the percentage of particles transferred initially increases as the particle size decreases. Furthermore, all particle sizes demonstrated a rapid initial loss.

Several relationships between the number of particles retained on the fabric and time were explored but the most satisfactory fit was obtained using the bi-exponential relationship de-

TABLE 1—*Mean and standard deviation of the number of glass particles retained on ten woollen fabric squares.*

Particle Size	Fired	Time, h					
		Initial	½	1	2	4	6
4 mm	40	0.5±0.7	0.2±0.6	0.1±0.3	0	0	0
1 mm	260	12.4±4.6	8.0±3.3	6.4±2.6	4.7±2.5	2.5±2.3	2.4±2.2
500 μm	520	70.8±23.1	37.1±17.6	26.4±16.7	13.9±9.2	9.7±4.8	8.0±4.0
250 μm	1040	343.5±62.0	78.9±48.5	47.6±32.8	33.2±35.6	13.9±7.5	8.2±3.8
125 μm	2080	491.5±39.5	224.6±48.3	129.3±28.2	89.4±17.9	32.3±8.3	26.8±7.9

TABLE 2—*Mean and standard deviation of the number of particles retained on ten denim fabric squares.*

Particle Size	Fired	Time, h					
		Initial	½	1	2	4	6
4 mm	40	0	0	0	0	0	0
1 mm	260	3.0±1.2	2.3±1.3	2.3±1.3	1.8±1.2	0.9±1.1	0.3±0.7
500 μm	520	1.8±1.5	1.0±1.1	0.4±0.5	0.3±0.5	0.3±0.5	0.2±0.4
250 μm	1040	14.8±2.2	8.6±2.1	4.3±1.4	1.3±1.6	0.5±0.8	0
125 μm	2080	514.5±43.4	331.1±28.9	145.2±25.9	78.9±20.7	42.7±8.6	32.7±9.9

duced from the postulates of the two-compartment model. In the case of wool, for each of the particle size ranges Table 3 shows that observed mean number of particles at different times and the predicted mean numbers obtained using the bi-exponential relationship. Examination of the differences between observed and predicted means and the residual sums of squares clearly indicate the model fits well. Similar results are shown in Table 4 for denim where, with the exception of particle size 125 μm, the bi-exponential model suitably describes the observed data. However there is some evidence that for small particle sizes, the goodness of fit of the model deteriorates as time increases. In the case of denim fabric the model was not fitted to the 4-mm particle size as there was no evidence of glass retention.

Tables 5 and 6 show values for the parameters A, α, B, and β, estimated using nonlinear least squares. In addition the tables show the calculated half-lives for ech of the particle size ranges. In the case of wool the α and β values are all negative which is consistent with zero retention as time progresses. However in the case of denim, for particle size ranges 500 and 125 μm a small positive value is obtained for β. This implies that the number of particles retained on the surface would initially decrease and thereafter increase with time. This is impossible in practical terms and arises from random variation in the parameter estimates. The small positive values of β should therefore be assumed to be zero.

Examination of the half-lives of the woollen fabric indicate that a maximum half-life of 1.109 h occurs with 1-mm particle sizes. Particle sizes greater and smaller than the 1-mm particle size give estimated half-lives considerably smaller than 1.019 h. For denim a similar phenomenon is observed as those particles with the longest half-life are in the 1-mm range. The retention of 1-mm particle sizes on denim has a half-life of 2 ½ times that of 1-mm particle sizes on wool. Of the remainder, with the exception of the 250-μm particle sizes the half-lives for corresponding particle size ranges were similar on both wool and denim. The five-day retention study for glass particles retained on woollen fabric gave results detailed in Table 7. They show that after five days it is possible to find particles on the fabric. Despite the difference in

TABLE 3—*Comparison of the observed with the predicted mean numbers of glass particles retained on the surface of woollen fabric.*

Particle Size	Time, h	Mean Number of Glass Particles			Residual Sum of Squares
		Observed	Predicted	Difference	
4 mm	0	0.5	0.50	−0.002	0.000
	0.5	0.2	0.21	0.016	
	1.0	0.1	0.09	−0.015	
	2	0	0.01	0.010	
	4	0	−0.003	−0.003	
	6	0	−0.0015	−0.001	
1 mm	0	12.4	12.37	−0.028	0.463
	0.5	8.0	8.14	0.143	
	1.0	6.4	6.23	−0.163	
	2	4.7	4.58	−0.124	
	4	2.5	3.01	0.509	
	6	2.4	2.02	−0.375	
500 μm	0	70.8	70.54	−0.264	6.874
	0.5	37.1	38.49	1.391	
	1	26.4	24.43	−1.966	
	2	13.9	14.76	0.863	
	4	9.7	10.04	0.335	
	6	8.0	7.61	−0.387	
250 μm	0	343.5	343.56	0.004	4.534
	0.5	78.9	78.81	−0.094	
	1	47.6	48.18	0.580	
	2	33.2	32.02	−1.129	
	4	13.9	15.34	1.444	
	6	8.2	7.36	−0.844	
125 μm	0	491.5	491.83	0.329	207.130
	0.5	224.6	221.86	−2.742	
	1	129.3	135.50	6.195	
	2	89.4	81.65	−7.751	
	4	32.9	41.44	8.537	
	6	26.8	21.49	−5.308	

the initial numbers transferred, the number of particles retained five days later in each of the particle ranges was small and did not exceed 3. Results for the mixed firing of equal amounts of 1-mm and 250-μm particles onto wool are given in Table 8. Calculated predicted values using the bi-exponential model are compared with the observed data in Table 9. Most of the retained particles were of the size range 250 μm and this is what would have been expected in view of the results in Table 1. This suggests that the 1-mm and 250-μm particle size ranges act independently. When the bi-exponential model was fitted to the data obtained from the combined particle ranges a small residual sum of squares of 17.954 was obtained, and the half-life was 0.356 h. Once again the bi-exponential model gave a good fit.

Discussion and Conclusion

For the study undertaken there is clear evidence that particle size and type of fabric influences the number of particles initially transferred. In addition particle size influences the pattern of retention thereafter. Less particles are initially transferred onto denim than wool. Particles of size 1 mm to 500 μm appear to be lost more slowly from both denim and wool than other particle sizes.

The elasticity of individual fiber strands of the closely woven denim material might have

TABLE 4—*Comparison of the observed with the predicted mean numbers of glass particles retained on the surface of denim fabric.*

		Mean Number of Glass Particles			
Particle Size	Time, h	Observed	Predicted	Difference	Residual Sum of Squares
1 mm	0	3	2.87	−0.128	0.115
	0.5	2.3	2.56	0.258	
	1	2.3	2.25	−0.052	
	2	1.8	1.68	−0.118	
	4	0.9	0.87	−0.033	
	6	0.3	0.42	0.117	
500 μm	0	1.8	1.82	0.019	0.029
	0.5	1.0	0.91	−0.094	
	1	0.4	0.52	0.118	
	2	0.3	0.29	−0.015	
	4	0.3	0.24	−0.064	
	6	0.2	0.24	−0.035	
250 μm	0	14.8	14.80	0.000	0.203
	0.5	8.6	8.55	−0.054	
	1	4.3	4.44	0.139	
	2	1.3	1.20	−0.102	
	4	1.3	0.09	0.413	
	6	0.5	0.01	0.006	
125 μm	0	514.5	522.46	7.959	2167.774
	0.5	331.1	299.87	−31.227	
	1	145.2	177.44	32.241	
	2	78.9	73.65	−5.251	
	4	42.7	35.66	−7.097	
	6	32.7	36.14	3.437	

TABLE 5—*Nonlinear least squares estimates for the model constants* A, α, B, *and* β, *and corresponding half-lives* $t_{1/2}$ *for glass particles retained on surface of wool.*

Particle Size	A	α	B	β	$t_{1/2}$
4 mm	0.5202	−1.6566	−0.022	−0.4494	0.401
1 mm	5.7385	−1.9779	6.633	−0.1978	1.019
500 μm	53.0637	−1.7322	17.1718	−0.1356	0.585
250 μm	276.7383	−4.9535	66.7651	−0.3676	0.187
125 μm	153.924	−0.3201	337.9057	−2.6189	0.423

TABLE 6—*Nonlinear least squares estimates for the model constants* A, α, B, *and* β, *and corresponding half-lives* $t_{1/2}$ *for glass particles retained on surface of denim.*

Particle Size	A	α	B	β	$t_{1/2}$
1 mm	−41.9637	−0.4889	44.8358	−0.4713	2.509
500 μm	1.5863	−1.7170	0.2330	0.0018	0.496
250 μm	16.9521	−1.3100	−1.6521	−45.248	0.607
125 μm	493.4063	−1.1892	24.0531	0.066	0.628

TABLE 7—*Retention of glass particles on woollen fabric over a five-day period.*

	Time, Days					
Particle Size	Initial	1	2	3	4	5
1 mm	13	2	0	0	0	0
500 µm	71	8	4	1	1	1
250 µm	344	8	2	2	2	2
125 µm	492	27	3	3	3	3

TABLE 8—*Mean and standard deviation of the number of glass particles retained from a mixed glass sample on ten woollen fabric squares.*

Particle Size	Time, h					
	Initial	½	1	2	4	6
1 mm	3.3±0.9	2.4±1.2	2.0±1.4	1.4±0.8	0.9±0.9	0.5±0.5
250 µm	285.4±37	113.5±22	68.0±22	49.8±10	31.3±15	27.4±5

TABLE 9—*Comparison of the observed and predicted mean numbers of 1-mm and 250-µm glass particles retained from a mixed glass sample on ten woollen fabric squares.*

Particle Size	Time, h	Mean Number of Glass Particles			Residual Sum of Squares
		Observed	Predicted	Difference	
1 mm	0	3.3	3.3	0.000	0.006
	0.5	2.4	2.42	0.020	
	1	2.0	1.96	−0.040	
	2	1.4	1.44	0.040	
	4	0.9	0.86	−0.040	
	6	0.5	0.52	0.020	
250 µm	0	285.4	285.40	0.000	18.371
	0.5	113.5	113.40	−0.100	
	1	68.0	68.40	0.400	
	2	49.0	48.17	−0.830	
	4	31.3	34.61	3.310	
	6	27.4	25.26	1.140	

been expected to produce a greater effect on the initial transference of glass particles than that of woollen fabric. With the exception of the 125- to 63-µm particles the numbers initially transferred to wool are always in excess of those transferred to cotton denim. However initial transference must also be related to the "pore" sizes that allow particles access to the interior of the fabric. In the case of cotton these pore sizes will be much smaller than those of wool. The tension in individual fiber strands when the initial impact of the glass particles occurs can also be expected to influence elasticity and pore size. Consequently, projecting particles onto loosely worn garments will not necessarily produce the same effect as projection onto tightly fitted clothing.

The explanation of glass retention in terms of a surface and interior compartment is supported by the experimental findings. However it is possible that the existence of an interior compartment arises from the force with which particles were projected onto the fabric. The model proposed should not be assumed valid for other modes of projection such as glass particles transferred by backward ejection when window glass is broken.

Other factors can be identified which may also account for the reported phenomenon such as the use of a point source to project the particles and the angle of impact which ranged from 73 to 90° in this study. Clearly more work is required to establish the important factors for accurately assessing the time of retention of glass particles on different types of fabric.

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