Experimental Verification of Failure of Amontons' Law in Polymeric Textiles

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Received 7 April 2003; accepted 18 September 2003

ABSTRACT: The dynamic friction of a variety of textile materials was studied and was experimentally proven that the frictional behavior of textile materials do not obey the Amontons' basic law of friction ($F/N = \mu$). Both woven and nonwoven materials with different fiber content and constructional features were used in the study. Results show that the dynamic friction–normal load relationship is not a straight line passing through origin. A statistical approach has been followed to prove the significance of the deviation from the Amontons' law. To the authors' best knowledge, the work reported in this article has for the first time experimentally proven the failure of Amontons' basic law of friction for polymeric textiles, using a novel approach. © 2004 Wiley Periodicals, Inc. J Appl Polym Sci 91: 3879–3885, 2004

Key words: polyesters; fibers; mechanical properties; surfaces; adhesion

INTRODUCTION

It is generally accepted that textile materials do not obey Amontons' laws of friction. Amontons' classical law of friction is based on the linear relationship between the friction force and the applied normal load. The failure of the Amontons' relationship between the friction force and the normal load necessitates the need for calculating the friction of fabrics at different applied loads.[1,2] The relationship between the friction force (F) and the applied normal load (N) can be conveniently represented by using the relationship

$$F/A = C(N/A)^n \tag{1}$$

where F is the friction force in Newtons; N is normal applied load in Newtons, A is the apparent area of contact in m^2, C is the friction parameter in Pa^{1-n}, and n is the friction index (nondimensional).

Wilson's experiments on a variety of fabrics have shown that the above relationship is valid for representing the friction force–normal load relationship.[2] Experimental investigations by Dreby,[3] Howell,[4,5] and Garlen[6] showed that the friction force–normal load relationship is not linear for textiles. Howell and Mazur used a power equation of the form $F = CN^n$ to represent the relationship between the friction force and the normal applied load, where F is the friction force, N is the normal applied load, and C and n are friction constants. Their experimental results were found to fit well with the above relationship when the value of n was less than 1.[5] Most recently, there has been a major upsurge in research on the surface mechanical properties of polymeric materials and textiles due to the need for a refined methodology for frictional characterization.[7–12] Ramkumar et al. studied the influence of knitted fabrics' structural variables such as the loop length and the yarn linear density on the frictional properties of rib knitted cotton fabrics by using a novel friction parameter.[7] Ramkumar has given a brief review on the deviations from Amontons' law of friction in textile materials.[1] Based on the fundamental studies, a refined friction factor has been derived and has been used to characterize the changes in the surface properties of enzyme treated cotton fabrics.[9] The refined friction factor is given by

$$R = C/n \tag{2}$$

where R is the friction factor in Pa^{1-n}, C is the friction parameter in Pa^{1-n}, and n is the friction index (nondimensional).

In another study, the refined factor was used to characterize the frictional properties of a set of needle-punched nonwoven fabrics.[12] Three different sets of

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Contract grant sponsor: U.S. Army SBCCOM.
Contract grant sponsor: Leather Research Institute at Texas Tech University.

Journal of Applied Polymer Science, Vol. 91, 3879–3885 (2004)

TABLE I
Material Details

Sample ID	Fabric type	Fiber content	Construction
1	Nonwoven	70% Cotton/30% polyester	Needle-punched nonwoven
2	Nonwoven	50% Cotton/50% polyester	Needle-punched nonwoven
3	Woven	Cotton	Twill 3 × 1
4	Woven	Cotton	Plain woven
5	Woven	Cotton/polyester	Plain woven
6	Woven	Cotton	Plain woven
7	Woven	Cotton	Satin 4 × 1
8	Woven	Cotton	Basket (2 × 1 duck)
9	Woven	Cotton	Plain (sheeting)
10	Woven	Cotton/polyester	Plain (broad cloth)
11	Woven	Cotton/polyester	Plain (sheeting)

cotton/polyester-blended fibers were needle-punched on the H1 technology needle loom. Lightweight needle-punched nonwoven webs weighing approximately 50 g/m^2 were developed. The sliding friction apparatus was used to measure the surface mechanical properties of nonwovens. Frictional forces were measured over a range of six different applied normal loads. Frictional forces measured at different applied normal loads were used to calculate the normalized friction factor, R. The novel friction factor, R, was able to distinguish the variations in the blend composition in the needle-punched nonwovens. An increase in the polyester component resulted in an increase in friction, which was reflected in higher friction factor, R values. Ramkumar and Roedel investigated the effect of three different needle-punching rates on the surface mechanical properties of H1 technology needle-punched webs.[11] Polyester fibers were needle-punched at 400, 600, and 1000 strokes/min. Results indicated that the friction force–normal load relationship can be conveniently expressed by using the power relationship. Frictional properties were characterized by using the novel friction factor, R. The effect of different needling rates was clearly reflected in the friction factor, R values. As the needling rate increased, frictional characteristics of the nonwoven webs increased, which was reflected in higher R values.[11] Most recently, Ramkumar et al. investigated the effect of different frictional sliding velocities on the frictional properties of two different needle-punched nonwoven substrates. Two different polyester nonwoven webs varying in weights were needle-punched on the H1 technology needle loom. The different sliding speeds used were 100, 500, 750, and 1000 mm/min. Results showed that at all sliding speeds investigated, friction force increased with the increase in applied normal loads. However, the coefficient of friction decreased with the increase in normal loads at all sliding speeds. This result indicates that the coefficient of friction is not a constant factor for nonwoven substrates and that the characterization of the friction of nonwoven webs by use of the coefficient of friction is not scientifically logical.[13]

As is evident from the above-mentioned discussions, it is not logical to characterize the frictional properties of polymeric materials by using the coefficient of friction μ. The coefficient of friction μ is the constant of linearity between the friction force and applied normal load. There is a plethora of literature available that briefs the deviation from the Amontons' classical law of friction ($F = \mu N$) for textiles.[1–18] However, to the authors' best knowledge there is a paucity of literature that clearly proves the deviation from the Amontons' basic law of friction in polymeric materials. It is extremely important to experimentally prove that it is illogical to represent the relationship between the friction force and the normal load as a straight-line equation passing through the origin. In this article, the authors have followed an experimental approach to prove the failure of Amontons' law of friction in polymeric textiles. The results have been validated by using a statistical approach.

METHODS

A set of 11 different fabrics was used in the study. The experimental method that was used to characterize the frictional properties is described in the later part of this section. Details about the materials used are given Table I. More detailed information on the samples was not possible as they were acquired from different commercial sources in very limited quantities. Furthermore, an elaborate description of the samples was not considered important as this article deals with the experimental verification of the failure of Amontons' law and not on the influence of fabric constructional features on friction.

Nonwoven fabrics were developed on the H1 technology needle loom. H1 technology is one of the modern developments in needle-punching nonwovens technology.[19] Texas Tech University is the first facility in the U.S.A. to house the modern needle-punching

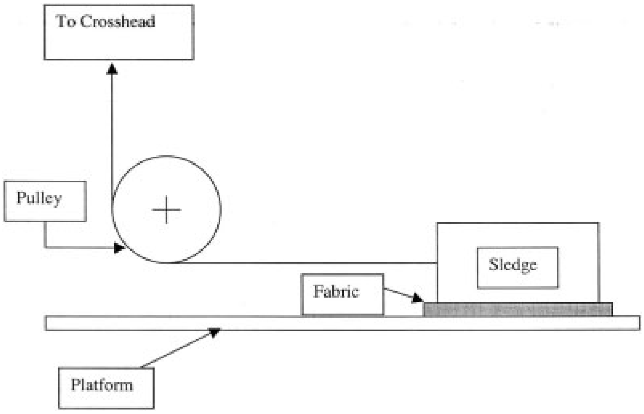


Figure 1 Sliding friction apparatus.

technology. H1 technology is a patented invention of Ernst Fehrer of Fehrer, AG.[20–22] The contoured needle zone in the H1 technology results in an oblique-angled needle penetration on fibers. Such a penetration results in longer needle paths and helps with better fiber orientation and fiber entanglement than the flat needling zone machine.[22–23] Roedel and Ramkumar have elaborated on the details of the H1 technology needle loom and the characteristics of nonwoven fabrics developed on H1 technology needle loom in another article.[12]

The sliding friction apparatus as shown in Figure 1 has been used to characterize the frictional properties of 11 different fabrics.

The sliding friction apparatus has been previously used to evaluate the frictional properties of a set of 1 × 1 rib knitted cotton fabrics.[7] The apparatus is similar to the one used by Ajayi.[14] In this study, a standard friction sledge with known dimensions was used. The sledge measured 5 cm in length and 4 cm in width. The initial weight of the sledge was around 36 g. One end of the sledge was attached to the load cell of the CRE tensile tester by an inextensible thread. The maximum capacity of the load cell of the tensile tester was

TABLE II
Frictional Values of Nonwoven Substrates

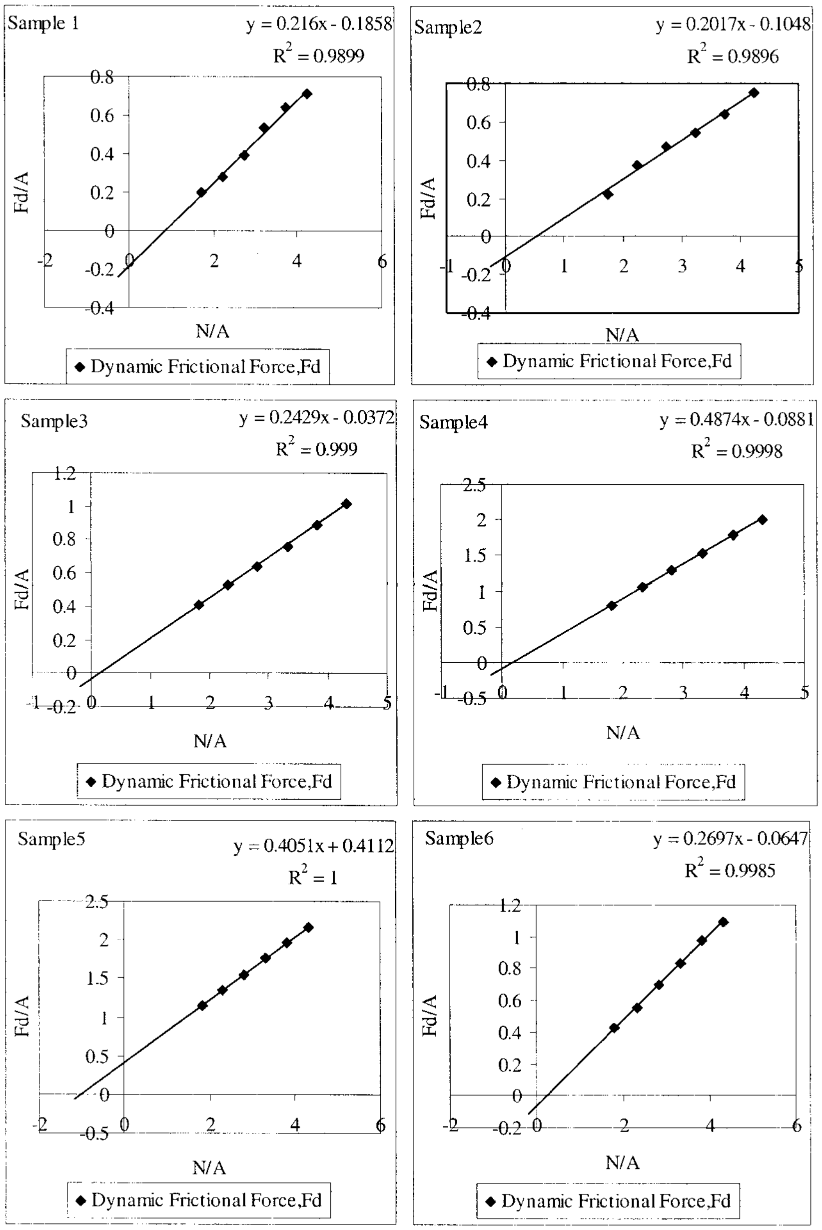
Sample ID	N/A (Pa)	F_d/A (Pa)
1	1.74	0.20 (0.77)
	2.24	0.28 (0.27)
	2.74	0.39 (0.19)
	3.24	0.54 (0.30)
	3.74	0.64 (0.50)
	4.24	0.71 (0.60)
2	1.74	0.22 (1.79)
	2.24	0.37 (1.55)
	2.74	0.47 (1.27)
	3.24	0.54 (0.90)
	3.74	0.64 (1.50)
	4.24	0.75 (2.70)

Values in the parentheses indicate standard deviation.
N/A, normal load/area; F_d/A, dynamic frictional force/area; Pa, Pascal.

TABLE III
Frictional Values of Woven Substrates

Sample ID	N/A (Pa)	F_d/A (Pa)
3	1.82	0.41 (0.25)
	2.32	0.53 (0.43)
	2.82	0.64 (0.64)
	3.32	0.76 (0.29)
	3.82	0.89 (1.04)
	4.32	1.02 (0.37)
4	1.82	0.79 (0.25)
	2.32	1.05 (0.29)
	2.82	1.29 (0.39)
	3.32	1.53 (0.21)
	3.82	1.78 (0.36)
	4.32	2.01 (0.67)
5	1.82	1.15 (0.15)
	2.32	1.35 (0.21)
	2.82	1.55 (0.09)
	3.32	1.76 (0.20)
	3.82	1.96 (0.17)
	4.32	2.16 (0.32)
6	1.82	0.43 (0.18)
	2.32	0.55 (0.29)
	2.82	0.70 (0.44)
	3.32	0.83 (0.35)
	3.82	0.98 (0.42)
	4.32	1.09 (0.44)
7	1.82	0.87 (0.11)
	2.32	1.08 (0.25)
	2.82	1.27 (0.28)
	3.32	1.47 (0.20)
	3.82	1.67 (0.25)
	4.32	1.87 (0.18)
8	1.82	0.91 (0.32)
	2.32	1.12 (0.27)
	2.82	1.33 (0.28)
	3.32	1.54 (0.47)
	3.82	1.76 (0.61)
	4.32	1.97 (0.86)
9	1.82	0.94 (0.99)
	2.32	1.15 (1.17)
	2.82	1.36 (1.21)
	3.32	1.59 (0.89)
	3.82	1.84 (1.43)
	4.32	1.99 (0.87)
10	1.82	0.75 (0.40)
	2.32	0.99 (0.58)
	2.82	1.24 (0.47)
	3.32	1.50 (0.43)
	3.82	1.71 (0.19)
	4.32	1.95 (1.30)
11	1.82	0.77 (0.21)
	2.32	0.99 (0.32)
	2.82	1.21 (0.11)
	3.32	1.46 (0.30)
	3.82	1.70 (0.32)
	4.32	1.91 (0.29)

Values in parentheses indicate standard deviation.
N/A, Normal load/area; F_d/A, dynamic frictional force/area; Pa: Pascal.

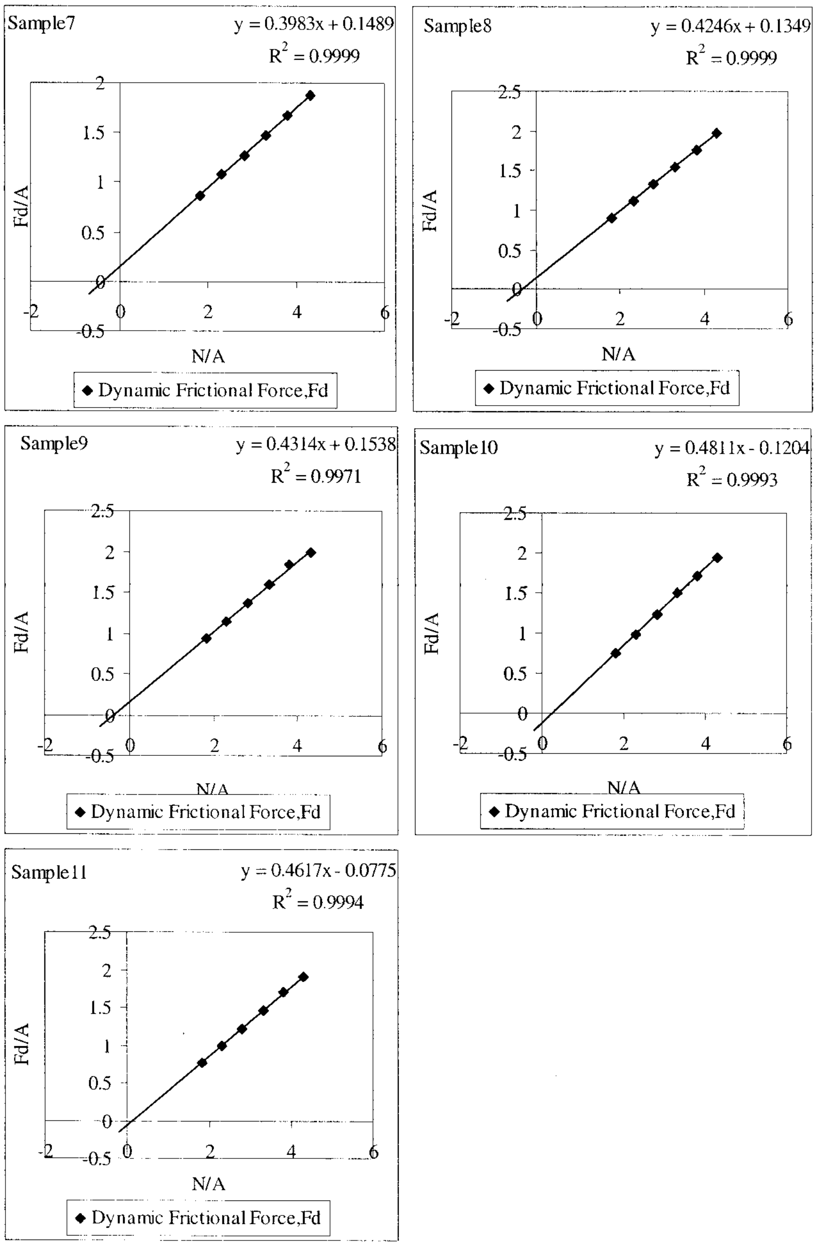


(a)

Figure 2 (a) Friction force versus normal load; (b) friction force versus normal load.

25 kgf. The experiment was conducted over a range of different applied normal loads. The minimum and the maximum loads used were around 36 and 86 g, respectively. The load was increased in steps of 10 g. Three repetitions were carried out at each applied load for the different substrates investigated.

The sliding friction apparatus was found to be a convenient tool to measure the friction forces at different applied normal loads. Moreover, the sliding friction apparatus is simple in construction and can be easily adapted to different tensile testers. The tensile tester used in this study is microprocessor controlled and helps with the storage of a vast amount of data from the friction experiments. The dynamic friction forces at different applied normal loads were measured for all the fabrics studied. As the dynamic friction force is the average of the friction forces measured at a number of places on the fabric during the sliding process, it was thought to be logical to use the dynamic friction force to validate the deviation from the Amontons' law of friction in polymeric textiles. The standard friction sledge slid on the fabrics across the filling (weft) in the case of woven fabrics and across the cross direction in the case of nonwoven fabrics. Experimental results are given in Tables II and III. Three repeats were carried out at each applied normal



(b)

Figure 2 (*Continued from the previous page*)

load and the average friction force values were used for further calculations. Dynamic friction force was normalized by the apparent area of contact. As is evident from the experimental results, the standard deviation values are high for the normalized friction force. The variations could arise due to inherent material variations, deviations in constructional features, and system variations during manufacturing. Furthermore, the normalization process results in higher standard deviations as the friction forces are normalized by a constant factor, which is the apparent area of contact. It is assumed that the apparent area of contact remains constant and the variations are associated with the friction force values.

Deviations from the Amontons' Law of Friction

Although the classical article by Wilson showed that the linear relationship between the friction force and normal load fails in textiles, the deviations from the linear relationship were not elaborated on in the article.[17] It is therefore important to experimentally prove the failure of Amontons' law of friction in textiles. According to Amontons' law of friction, for materials that obey the basic law of friction, the relationship between the friction force and normal load should be constant. Mathematically, based on Amontons' law of friction, the friction force–normal load relationship ($F/N = \mu$) is a straight line passing through the origin. For all the fabrics investigated in this study, it has been found that the relationship between the dynamic friction force and normal load does not pass through the origin [Fig. 2(a, b)]. Also, it is evident from the correlation of determination (R^2) values that the R^2 values are significantly high (>0.98), indicating that the equation is a straight line and does not pass through the origin. The simple methodology adopted in this article proves beyond doubt that the relationship as shown in eq. 3 is not a valid relationship to represent dynamic friction force–normal load relationship

$$F/N = \mu \tag{3}$$

where F is the friction force, N is the normal applied load, and μ is the coefficient of friction (constant of linearity).

Statisticsal verification of the failure of Amontons' Law of Friction

As delineated in the introduction, this article endeavors to prove that the basic Amontons' law is not valid in polymeric textiles. Regression analysis has been used to represent the straight-line relationship between the dynamic friction force and the normal load. It was possible to obtain the statistical *P* values by using regression analysis. The *P* values have been used to verify the null hypothesis that the equation is a straight line passing through the origin (i.e., there is no intercept). Alternate hypothesis is that the Amontons' relationship is not valid in the case of polymeric textiles. The significance level *P* of 0.05 has been used as the standard default significance level for accepting or rejecting the null hypothesis. The thumb rule followed was that if the calculated *P* (Table IV) is higher than the default significance level, then the null hypothesis is accepted. This means that there is no intercept term required in the dynamic friction force–normal load equation. Obtained experimental results show that in all fabrics investigated, *P* values were lower than the default significant *P* value, indicating that there is a need for the intercept term in the friction equation. In addition, in the cases of samples 5, 7, and 8, *P* values were very small, which strongly proves that the Amontons' friction law has failed in these fabrics. The statistical methodology adopted in this study provides solid evidence experimentally that polymeric textiles fail to obey Amontons' basic law of friction.

TABLE IV
Friction Force versus Normal Load Intercept Values (and *P* values)

Sample ID	*P* value dynamic	Intercept value dynamic
1	0.005	−0.191
2	0.031	−0.098
3	0.036	−0.043
4	0.002	−0.085
5	8.29E−08	0.417
6	0.017	−0.072
7	2.01E−05	0.160
8	1.06E−05	0.141
9	0.014	0.152
10	0.004	−0.112
11	0.012	−0.079

CONCLUSION

The sliding friction apparatus has been conveniently used to evaluate the frictional properties of a set of woven and nonwoven fabrics. The relationship between the dynamic friction force and the normal load applied is straight line that does not pass through the origin. The relationship shows that Amontons' basic law of friction is not obeyed in polymeric textiles. The work adopted a statistical approach to prove the deviation from the Amontons' law. Statistically significant *P* values obtained from the regression analysis of the dynamic friction force and the normal load applied proved that the relationship is a straight-line equation that does not pass through the origin. The *P* values were significantly lower than the default significance level of 0.05, proving that the equation makes an intercept. The work has utilized a novel statistical approach to disprove the Amontons' physical law in the case of polymeric textiles. Results obtained clearly show that it is both physically and mathematically illogical to characterize the frictional properties of polymeric textiles by using the coefficient of friction μ values.

Seshadri Ramkumar gratefully acknowledges the U.S. Army SBCCOM for funding research on nonwoven protective substrates, of which the work reported in this article forms a part. Ranjeet Rajanala gratefully acknowledges the Leather Research Institute at Texas Tech University for providing a research assistantship.

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