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Office of The Quartermaster General
Military Planning Division
Textile & Leather Products Section

TEXTILE SERIES - REPORT NO. 52

THE RELATIONSHIP BETWEEN THE STRUCTURAL GEOMETRY OF TEXTILE FABRICS AND THEIR PHYSICAL PROPERTIES

Aug. 1948

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LITERATURE REVIEW

BY

STANLEY BACKER

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The Office of Technical Services
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FOREWORD

During the war, numerous improvements to military textile items were shown to be possible as a result of modification of fabric construction or the development of functional finishes. However, under the pressure of procurement and substitution problems there was little time for a concentrated and well-planned investigation of the effect of the many details of fabric geometry upon the subsequent behavior of that fabric in a textile end item.

This is the first in a series of papers to be issued by the Quartermaster Corps discussing the importance of fabric geometry in the development of more utilitarian and serviceable textile materials. It is a literature review which shows the relationship between the structural characteristics of fabrics and various functional characteristics, such as breaking strength and elongation, tear resistance, thermal insulation, abrasion resistance, and gas permeability. Other papers will soon follow, dealing with the experimental programs conducted by the Quartermaster Textile Laboratories at Philadelphia or by laboratories studying this problem under Army auspices.

S. J. KENNEDY
Research Director
for
Textiles, Clothing and Footwear

August 1948

THE RELATIONSHIP BETWEEN THE STRUCTURAL GEOMETRY OF TEXTILE FABRICS AND THEIR PHYSICAL PROPERTIES

I Literature Review

A. Introduction

B. Breaking Strength and Elongation

C. Tear Resistance

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E. Abrasion Resistance

F. Gas Permeability

G. Quartermaster Studies

The Relationship Between the Structural Geometry of a Textile Fabric and Its Physical Properties

I Literature Review*

by

Stanley Backer

A. Introduction

The production of textile fabrics to meet the requirements of industrial, household, and apparel uses is a threefold problem involving:

(1) selection and cultivation or manufacture of a base fiber possessing the properties desired in the end product.

(2) construction of materials which enhance the characteristics of the fibers used through the medium of the form or geometry of the yarn and fabric.

(3) modification of the intrinsic fiber properties or the structural geometry of the textile by chemical treatments.

The first and last of these phases have had the benefit of the concentrated efforts of textile research engineers, physicists, and chemists for many years and the results are evident in the existence of such widely used man-made fibers as viscose rayon, nylon and acetate rayon, and such well known finishing effects as shrink resistance, dye fastness, water repellency and crease resistance.

The second phase, which embodies the building of fabric structures to enhance available fiber characteristics or create entirely new properties in the finished item, has been the subject of practical mill experimentation since the days of the hand weavers. However, there is little evidence in the early literature of systematic engineering research directed towards improvement of the form or geometric configurations of yarns and cloths until about 1930.

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* Part of M.I.T. thesis bearing same title, prepared in Feb. 1948 under the direction of Prof. E. R. Schwarz.

Since then, increasing interest has been shown in the structural engineering involved in textile fabrication, with several papers reporting on modifications of fabric properties with systematic variations in their form factors.[10,31,32,33] Peirce [26] at the Shirley Institute generalized the changes in yarn and fabric form, on the basis of geometric similarity, and thus was the first to establish the fundamental principles of textile structures.

The geometry of a textile fabric is determined by the mechanical processing to which the material is subjected from fiber state to finished cloth. Among such processes are carding, combing, spinning, weaving, milling, shearing, and napping. The practical geometry of the cloth is described by form factors which are in common use throughout the textile industry. These include:

(1) yarn count
(2) yarn twist
(3) threads per inch
(4) weave
(5) crimp

Since each of the factors listed, with the exception of weave, may be varied in either warp or filling directions, the problem of predicting the mechanical behavior of fabric structures becomes one involving up to nine variables, some of which are independent, while others are related either throughout their ranges or merely at their limits.

The large number of characteristic "textile" properties mentioned in the recent literature arise from the two fundamental fabric elements, fiber and air. Many of the properties of textiles which govern their conformance to technical specifications are dependent for the most part on the yarn network; these include breaking strength, thickness and weight. Strange as it may seem, an equally large group of fabric qualities are more dependent upon the pore structure than upon the yarn network; these include resistance to flow of liquids, gases, and light. A third set of attributes relies to a considerable degree upon an interchange in yarn and interstice geometry, and it is here that the textile differs from most other fabricated items; these include tear resistance, fabric drape, and sewability.

B. Breaking Strength and Elongation

The breaking strength of a textile fabric is enhanced by increase in the strength of its component yarns and in the number of such yarns gripped between the jaws of the machine. Essam [10]

extends the elementary relationship stated above, in a study of four weaves constructed with four degrees of openness and with yarns of four twist multiples. He concludes that weave structure is a controlling factor in the determination of crimp, which in turn influences the extensibility of the fabric in a given direction. The degree of yarn twist affects the fabric elongation, for when tightly twisted yarns are woven in a close texture there is an apparent loss of extensibility. Single yarns are also tested for breaking strength and multiple strengths for each system of fabric yarns (unwoven) are computed. These data are compared with the actual fabric strength values and the differences are attributed to the type of weave, the texture, and the yarn twist.

Schiefer, et al [31] discuss the effect of warp and filling twist on breaking strength, elongation, and fabric assistance for plain weaves and 2/2 basket weaves. They observe no consistent differences in fabric properties as a result of change in yarn twist direction, however, as yarn twist multipliers are increased the corresponding directional breaking strengths of the fabrics increase to a maximum point, then decrease with very high twist multipliers in a manner similar to the behavior of single yarns. Peak fabric strengths occur at twist multipliers of 4 to 4.75 in warp and filling. The investigators define fabric assistance as the difference between the strengths of skein yarns and the same yarns woven into a cloth structure, expressed as a percentage of skein yarn strength. It is shown that fabric assistance decreases in general with an increase in twist multipliers until a minimum is reached, whereupon further increase in twist multipliers are accompanied by greater fabric assistance. The maximum and minimum points of these two curves (fabric strengths vs. twist multipliers and fabric assistance vs. twist multipliers) occur at the same twist multiplier. Greater fabric assistance in the plain, as compared to the basket weave, is attributed to the greater number of yarn interlacings in the plain weave. It is noted that the elongations of the cloth exceed those of the yarns and this effect is attributed to crimp; it follows that the plain weave has greater extensibility than the basket weave. Cloth elongations increase with higher twist multiples.

In a later study Schiefer, Taft, and Porter [32] vary the number of warp and filling yarns per inch and evaluate the effect on mechanical properties of the fabric. With increased texture higher crimps occur, resulting in greater extensibility. Again the plain weave shows greater elongation than the basket weave. The investigators find that increased fabric assistance occurs with denser weaves until a maximum is reached. In some fabrics, particularly the plain weave, the assistance falls off with further increases in texture. In general, the plain weave furnishes the greatest fabric

assistance, which confirms the findings of Essam. In a second series of fabrics, increases in filling twist are accompanied by little or no change in warp elongation, but marked increases in filling elongation are observed. The warp breaking strength is unaffected but the filling strength varies in a manner similar to the strengths of single yarns of varying twist multipliers.

Morton and Williamson [24] examine the influence of varying warp tensions on the mechanical properties of plain weaves varying in cover factor from 13.2^2 to 16.2^2. Varying warp tensions gives rise to slight changes in filling crimp for the fabrics under study but warp crimp is significantly affected in the fabrics of 14 x 14 cover and over. (The 13 x 13 cover fabric is predominantly filling crimped and, therefore, the change in warp crimp is small.) As a result of increased weaving tensions, warpwise fabric elongation is considerably reduced. It is pointed out that breaking extension depends primarily on crimp in the longitudinal threads and their extension properties. Cloth strength is affected by the degree of binding of the cross threads which aids interfiber frictional forces and contributes to the restriction of the region of breakdown. The degree of binding is dependent on the density of the weave. In weaves of 14 x 14 cover factor and higher, positive fabric assistance is observed. As tensions during weaving are increased the resultant fabrics (with the exception of the 13.2 x 13.2 cover) undergo an increase in breaking strength.

Peirce [26,27] comments on crimp distribution as a factor of prime importance in determining fabric strength and elongation. The straightening of longitudinal threads during the test applies compressive forces at the points of contact with the cross yarns. If the cross yarns jam before crimp exchange is complete, reduction in fabric strength and extensibility will result. Peirce's formulae are are extended by Womersley[36] who takes into consideration the geometry of fabric structure to predict the stress-strain relationship of cloth. General equations are furnished to describe the position equilibrium of a cloth subject to tension at its edges and hydrostatic pressure normal to its surface.

Certain of the principles outlined above are used to advantage by Hotte [18] to predict the breaking strength and elongation of combination fabrics such as are used in balloons. Hotte varies warp crimps by systematically increasing filling textures. He then measures breaking strengths and extensions of individual fabrics which are later to be layered in a balloon combination. In subsequent fabric examinations the breaking extension of the least extensible component fabric is taken to be the ultimate elongation of the combination. From the individual stress-strain curves the resistance of each component

material to this extension is determined. Hotte shows the close correlation which exists between the sum of the loads thus borne by the individual fabric components and the total breaking load of the balloon combination.

C. Tear Resistance

Tearing of fabrics in service is usually preceded by fortuitous snagging which is difficult to reproduce in the laboratory. Laboratory tear tests in common use today are the Trapezoid, Tongue, and Elmendorf methods [2]. The geometric factors influencing tear resistance of textile fabrics, when measured according to these standard methods, are studied empirically by Schiefer, Cleveland, Porter and Miller [31]. As in the case with air permeability, they conclude that a fabric which is closely woven, firm, and has a large number of thread interlacings per unit area and short floats has lower tear resistance than a cloth of the same weight which is loosely woven, sleazy, and has a small number of thread interlacings per unit area and long floats. It is of interest to note the linear relationship between Schiefer's values for tear resistance and the sum of warp and filling crimp. This relationship is indicative of the importance of so-called "interchange geometry" in predicting tear resistance. In another paper, Schiefer [32] notes the increased tear resistance of the basket weave over the plain weave, attributed to the greater freedom of movement of yarns in the former pattern. Increase of warp and filling texture does not appear to alter tear resistance. (This statement conflicts with later findings.) However, increase in filling-twist multiple is accompanied by higher tear values across the filling as a result of greater yarn elongation and more freedom of yarn movement due to the reduced diameter.

Krook and Fox [21] attribute the breakdown occurring in the tongue tear test to the recurring formation of "pseudo jaws" which build up at a rate related to the number of yarns per inch (in the direction along which the tearing action is taking place). In the case of the greater number of longitudinal yarns the more rapid occurrence of the "pseudo jaw waves" does not permit gripping of as large a number of transverse yarns as was the case formerly; the tearing load is, therefore, carried by fewer yarns, resulting in lower tearing strengths. Increasing the number of yarns being torn per inch serves to build up the jaws more rapidly by providing more contact points, but at the same time, furnishes more yarns in the jaw width. The reduction in tear strength which follows is attributed to the facts that (1) the yarns in the pseudo jaws rupture progressively in groups, (2) the area of contacts, and therefore the friction effect, decreases with higher textures, and (3) a number of the contact points do not contri-

bute to the effective portion of the pseudo jaws. Correlations between filling textures for the given structure and tear-resistance values are computed in the study.

Hager, et al, [13] analyze the mechanism of the trapezoid tear test described in ASTM manuals [2]. Their technique parallels that of Hotte [18] in estimating the strength of a combined structure based upon the load-elongation characteristics of the components. The trapezoid test is shown to be in effect a tensile test of yarns of varying initial lengths. Maximum elongation and, therefore, rupture, occurs in the shortest yarn, that one located at the edge of the tear near the initial slit. However, before this rupture condition is reached, partial elongations are undergone by the adjacent yarns in accordance with their geometric locations and each stressed yarn resists separation of the machine jaws to the extent of its constant of elasticity. Summing the resistance offered by all such yarns, including the one at the point of rupture, the investigators arrive at an expression for prediction of fabric tear resistance.

D. Thermal Resistance

The warmth of textile fabrics is without question the prime factor governing the type of clothing worn in temperate and arctic climates. So long as temperature differentials exist between the skin and the surrounding air, transfer of body heat will take place, resulting in discomfort which is related to the rate of heat loss. In functioning as a resistor to heat flow, cloth behaves as do ordinary building materials in the conduction, convection and radiation of heat; however, the proximity of the warm moist skin imposes additional requirements on clothing materials which are not ordinarily considered by the mechanical engineer.

Low-density materials, such as textiles, contain a large proportion of air within their total structures. Heat transmission through media of this type is, therefore, primarily dependent upon the resistivity of the air layer. The lower the proportion of fiber to air the higher will be the resistance to heat flow of the cloth. The limiting insulation is that of a layer of air equivalent in thickness to the textile material, assuming, of course, static conditions with no convection currents. In practice the chief function of the cloth is to trap an air layer (with high resistance), thus preventing circulation of air currents around the subject. Opposing requirements of high porosity (low density) and low permeability (negligible convection) are satisfied in combination fabrics consisting of a thick porous lining and thin, tightly woven outer cloth. Numerous investigations have led to this development and a few of these are reviewed to illustrate the

general effect of fabric geometry on heat flow properties. In this review little attention will be paid to the instrumentation involved. More detailed information concerning the methods of measuring thermal conductivity is available in the reports of Haven [16], Black and Matthew [6], Rees [30], Cleveland [8], and Baxter [5].

As has been indicated, the layer of dead air space in a textile material is of great importance in determining heat flow. Conditions of tests which tend to disturb this layer must be carefully controlled to prevent reflection of such variables in the test results. Included among these factors are wind velocity impinging against the fabric surface and tension or compression on the sample imposing a change in its geometric structure. Niven and Babbitt [25] investigate the effect of wind velocities on the thermal insulating values of some clothing during wear and find that the tightness with which a combination of fabrics is worn is of more importance than the material. Tightness of textiles of low density is accompanied by compression and loss in thermal insulation value. This has been reflected in the complaints from army troops stationed in the north to the effect that winter "Long Johns" are poor insulators.

Rees [30] collects data on a large variety of fabrics of varied fiber content and demonstrates the dependence of heat loss upon one geometric consideration, that of thickness. In a similar comparison of weight vs heat loss, he reports a general relationship to exist with points more widely scattered than in the thickness plot. Since increased thickness is generally accompanied by greater weight, this relationship is logical. It is also found that, in general, low-density fabrics have higher resistance than high-density materials, for in the denser fabrics the fiber conduction losses assume greater proportions. Increasing wind velocities during test cause greater heat losses in all cases, the low-textured material undergoing the greatest change in heat flow. Single blankets which have relatively poor insulating qualities at high wind velocities are remarkably improved by addition of a light, tightly woven linen cloth. Finally, in the surface structure, smoothness vs roughness is noted to be a contributing factor in causing the initial chill or cold feel of fabrics when brought in contact with the skin.

Hock, et al [17] show the area of contact between fabric and skin to be a major factor contributing to the chilling effect of moist fabrics. The results of their experiments show progressive

improvement of fabrics with respect to chilling as their wool content is increased, thus effecting a more lofty structure and rougher surface. The superiority of certain types of structures is evident. This work suggests a means for constructing a fabric with minimum chilling effect by use of unbalanced crimp and varied counts in the warp and filling directions to promote a ribbed effect with little contact surface area.

In a study of the properties of household blankets Schiefer, et al [33] confirm the finding that thermal conductance of fabrics is independent of the kind of fiber. The reciprocal of thermal conductance, or thermal resistance, was found to be related linearly to thickness as shown:

$$\text{Thermal Resistance} = \frac{1}{\text{Conductance}} = 3.0G + 0.63$$

where G is the thickness in inches at pressure of 0.10 lb/sq.in. and conductance is expressed in B.T.U./°F. Hr. ft^2.

Hamlin and Warner [15], studying 90 varying knit constructions, show thermal transmission to be inversely proportional to thickness and weight. They point out, however, that fabrics having a given weight can be made in a considerable range of thicknesses. In the fabrics constructed, thickness and weight are directly related, thus accounting for the correlation between weight and thermal values. Similarly, the thicker fabrics are less permeable to air and the data accordingly show higher transmission (thermal) with higher air permeabilities even though the tests are conducted under static air conditions.

Fletcher [11], in her studies of knitted fabrics, treats the subject of thermal insulation in a manner similar to Schiefer's work on the subject. Plotting the reciprocals for thermal conductance, or thermal resistance, against thickness, G, at 0.1 pound/square inch, she obtains a straight line represented by

$$\text{Thermal Resistance} = 3.85\ G + 0.61$$

which closely resembles the relationship derived by Schiefer.

In an ASTM sponsored program Backer and Winston [4] study the ranking of thermal-transmission values reported by several laboratories on twenty-four woolen materials varying in structure. Of the numerous properties listed, thickness evidences the closest relationship with thermal-insulating values. Pearson's coefficient for comparison of these two parameters varies from .94 to .99.

Results of thermal tests conducted by the Quartermaster Corps [4] during the war have been collected and some two hundred test figures are available representing samples which range from light-weight flannels to heavy pile fabrics of both cotton and woolen materials. The physical properties of thickness, weight, density, and air permeability have been tabulated and an attempt made to relate the structure of the fabric to its warmth as measured in the QM laboratory. The sole significant relationship noted is again that between thickness and thermal values.

Larose [22] investigates the effect of closeness of weave and thickness upon thermal values of fabrics and shows that in winds up to 6 mph there is little disturbance of the air behind a thin fabric covering a heavy pile material (for air permeabilities up to 50 $ft^3/ft^2/min$ at .5 inches of water). The sole effect up to this point is to change the resistance of the surface boundaries, which occurs at low velocities. From 6 to 30 mph the reduction in thermal resistance is practically proportional to wind velocity for covers of low permeability. More permeable fabrics lose more thermal resistance in the range of 6 to 24 mph then flatten off in the range of 24 to 30 mph. The open structure of the underlayers of fabric is seen to affect thermal resistance when higher velocities are used with more permeable cover fabrics. Variations in wind direction appear to affect thermal resistance in accordance with the perpendicular vector to the fabric surface. However, this relationship does not hold at low wind velocities. Larose also shows loss in thermal resistance as a result of change in fabric thickness due to air pressure. All results reported for the fabrics are corrected for boundary air resistance and compression due to wind pressure.

Relationships plotted by Baxter [5] show thermal-insulating values to be linearly related (approximately) to thickness up to 1 cm. Where materials exceed this thickness the slope of the T.I.V. vs. G curve falls off rapidly and appears to become horizontally asymptotic. Surface emissivity is shown to be of major importance in thin fabrics but its effect diminishes as thicker materials (above .5 cm) are considered. Emissivities are dependent on radiation and convection. The former is dependent on the fibers of the fabric and upon dyeing while the latter is a function of the geometric structure of the surface. Rough surfaces possess lower emissivities than corresponding smooth surfaces and this difference is even more pronounced with increased wind velocities.

Goddard and Van Dilla [12] experiment with air layers to determine the feasibility of constructing an inflatable sleeping-bag pad. They find that air layers reach maximum insulation at 1/2 inch after which convection currents minimize the effects of increased

thickness. Bounding materials make no difference in the values recorded except where open structures are used. Reduction of convection currents in the air layers is accomplished (with increased thermal insulating values) by inclusion of triangular shaped baffles in the air space. These investigators of the Quartermaster Climatic Laboratories indicate successful increases of insulating values of air layers by includion of a minute amount of waterfowl down in the layer. This principle is used in experimental pads which are enthusiastically received and highly praised by users in the arctic and wet, cold regions.

E. Abrasion Resistance

While the general subject of wear resistance or serviceability of textile materials is of great interest, it is more in keeping with the nature of this study to limit discussion of fabric "wear" to the mechanical abrasive attrition of textiles as influenced by cloth geometry. The literature contains numerous reports on studies of abrasion-testing techniques (4) and tests therewith, but when mention is made of specimen properties, it is invariably concerned with the fiber content. Nevertheless, there are a few scattered references made to fabric geometry as is illustrated in this section.

Peirce (27) speaks of avoiding the ribbed effect by control of geometric structure in order to enhance the abrasion-resistance qualities of fabric. Simon (34) underscores the importance of the direction of abrasion and recommends orientation of the lining fabrics of men's apparel in the direction which will offer greatest resistance to repeated rubbing during use of the garment.

Kaswell (19) introduces the "form factor" in abrasion testing, including in this term yarn size, twist, diameter; fabric weave; picks and ends per inch; per cent warp and filling on the surface; and float length. He states that a fabric surface which has high abrasion resistance in one abrasion and test direction (tensile test used as a means of evaluating damage), has poor abrasion resistance in the opposite abrasion and test direction. Thus, what is gained from form factor in one direction is lost in another. By use of photomicrographs the yarn system which predominates at the wearing surface is identified and the direction of abrasion is noted. Assuming fiber and finish to be the same, predictions of abrasion resistance may then be made. Results of tests on the Taber and M.I.T. machines are empirically weighted to account for the direction of wear and strength testing. Weighted results are found to correlate well with the values obtained in field tests on the Combat Course of the Quartermaster Corps.

Unpublished data resulting from tests conducted at the Quartermaster Laboratories also show the influence of geometry on abrasion resistance. The effect of direction of abrasion is illustrated in a parabolic curve relating angle of rubbing (measured from the warp direction) and residual strength after an arbitrary number of wear cycles. High points of the curve occur at 0° and 180° while minimum residual strength is noted at 90°.

Tait (35) reports on laboratory abrasion tests of a series of rayon linings varying successively in threads per inch and yarn diameters. A semilog relationship is here indicated between the warp threads per inch of warp-flush twills and the number of wear cycles to a visual endpoint. Tait also shows that longer wear as measured in the laboratory results from larger warp diameters.

F. Gas Permeability

Gas permeability (or air flow as commonly measured) is described as the rate of flow of a gas under a differential pressure through an area of the material. The geometric factors which influence this flow have been studied by numerous investigators on both an empirical and theoretical basis. Clayton (7) carries out a series of experiments to show the change in air flow with fabric form. In lieu of reporting total air permeability, AP, Clayton multiplies measured values by the cloth thickness to give sectional permeability, AP_s. With all other factors constant, he varies the twist factor of the filling yarn and finds a linear relationship between air permeability and twist. Increase in picks per inch from 35 to 65 results in linear decrease in the AP_s of a plain-weave fabric (141 ends/inch, 44's warp, 50's filling, and filling crimp 3.5%); beyond 65 picks per inch the curve flattens out indicating approach to complete closure. A straight-line relationship was noted between AP_s and filling count as the filling yarns were increased in size in a plain-weave construction with 141 ends/inch, 74 picks/inch, 44's warp and 3.0% filling crimp. In a final series Clayton maintains a constant cover factor by varying filling count and the number of picks per inch. A log relationship is shown to exist between the AP_s and each of these variables. This result is at variance with Peirce's (27) statement that flow resistance is primarily a function of warp cover factor, provided the weave is firm enough to hold the close warp yarns firmly in place. However, Peirce further qualifies his statement pointing out that flow is proportional to the pressure drop per unit thickness for any shape cross section.

Draper (9) measures a limited number of fabrics on a device of his own design and concludes qualitatively that AP is directly proportional to the yarn twist and looseness of weave and inversely related to the texture, the amount of carding, the yarn diameters and the extent of fabric felting where woolen materials are concerned.

Schiefer, et al (31) have produced a set of 42 fabrics of similar yarns (warp 57's, 4.0 T.M. and filling 60's, 2.6 T.M.) with a thread count in the loom of 90 x 90. Varied weaves are used in manufacture of the fabrics, including plain, twill, rib, mock leno, basket, sateen and combinations of these patterns. As a result of a study of the physical properties of these fabrics it is concluded that fabrics which are closely woven, firm, and have a large number of thread interlacings per unit area and short floats will have lower air permeability than cloths of the same weight which are loosely woven, sleazy and have a small number of thread interlacings per unit area and long floats. Schiefer's conclusions have been reaffirmed in the data of Quartermaster studies which indicate that for a given texture sateens possess the highest permeabilities followed in order by the HBT, HBT-Modified, Oxford and Plain weaves.

Rainard (29) uses the following relationship to study the air permeability of denims, twills, sheeting, pique and plain weaves:

$$F_1 \overline{AP} + F_2 = \frac{Pa'}{P}$$

where $\overline{AP}$ is the air permeability of the material and Pa is the pressure differential. The slope F_1 of this curve is stated to be dependent on the pore radius and the number of pores per square inch of fabric and is independent of the thickness of the fabric. F_2, the intercept, is dependent on the pore radius, the number of interstices per inch and the fabric thickness.

Many of the studies cited point to the effect of (1) fabric thickness, (2) pore size, and (3) the number of pores in a given area, upon the air permeability of a given cloth. The first and third factors can be measured without difficulty. Pore size, however, presents a problem which is difficult of flow analysis. Investigations have been conducted on the effects of orifice dimensions (1) on fluid flow and study has been made of the flow characteristics of equal area orifices, but with varying perimeters (23). Work of this nature has led to the use of hydraulic radii as a bridge between geometric fig-

ures (28). However, nothing as weird as the interstice shapes which exist in a textile fabric has been reported on. Careful consideration of the geometry of fabric pores is warranted if prediction of flow properties is to be made on the basis of fabric construction. This matter is dealt with at length in a later paper.

G. Quartermaster Studies

As a major consumer of a wide range of textile fabrics, the Quartermaster Corps has taken an active interest in the effect of construction upon the physical and mechanical properties of cloth. Several research and development programs initiated early in 1946 (20) are directed towards improvement of the functional characteristics of Army fabrics, such as, water, wear, and shrink resistance. One of the major problems of each of these investigations is the effect of fabric structure upon the pertinent property. In two of these projects (wear and water resistance) a wide range of materials has been produced under controlled conditions to permit evaluation of the effects of the variable elements of cloth geometry both individually and in combination.

Nominal data for the series of materials* prepared in connection with the wear-resistance program have been previously outlined (3). As expected, it was found that the constructions as determined from physical analysis of the actual fabrics differ from the previously published plans. In lieu of listing corrections at this time, it is planned to submit the revised data in later discussions of specific properties as influenced by fabric structure.

The fabrics* prepared under the water-resistance program cover a wider range of weights than those described in the conference on Quartermaster Research (3). Whereas the "wear" series consisted for the most part of one inch staple cotton and carded single ply yarns, the "water" series was manufactured of 1 1/4 inch staple and combed mercerized three-ply yarns. The difference in approach in the two programs was based on practical considerations. The "wear" series was built around the Army's standard work garment fabric, 8.5 ounce herringbone twill, while the "water" series was based on the constructions recommended by workers at the Shirley Institute for highest water resistance, and on the Army's standard nine ounce oxford. A summary of the systematic variations in the "water" series is presented in Table I.

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* Manufactured under the supervision of the Institute of Textile Technology, Dr. L. Larrick project supervisor.

Table I

Experimental Fabrics Constructed as Part of an Investigation of Water Resistance of Textiles

Series	Constant Factors K_1	K_2	T_1	T_2	β	Range of Weights ounces per square yard						
IA	30	15			$\sqrt{1}$	5.5	6.7	7.8	9.5	11.0	13.5	19.0
IB	30	15			$\sqrt{3/4}$	5.7	7.0	8.1	10.0	11.5	14.1	20.0
IC	30	15			$\sqrt{1/2}$	6.2	7.6	8.8	11.0	12.4	15.2	21.5
IIA			30	15	$\sqrt{1}$	5.5	6.7	7.8	9.5	11.0	13.5	19.0
IIB			30	15	$\sqrt{3/4}$	5.6	6.9	7.9	9.7	11.2	13.8	19.5
IIC			30	15	$\sqrt{1/2}$	6.0	7.3	8.5	10.4	11.9	14.6	20.2
IIIA	30			15	$\sqrt{1/2}$	5.5	6.7	7.8	9.5	11.0	13.5	19.0
IIIB	30			15	$\sqrt{3/4}$	5.9	7.2	8.3	10.2	11.8	14.4	20.4
IIIC	30			15	$\sqrt{1/2}$	6.6	8.1	9.4	11.5	13.2	16.2	22.9

Where

K_1, K_2 are the warp and filling cover factors respectively, where K is the ratio of the number of yarns per inch to the square root of the yarn count (26).

T_1, T_2 are the warp and filling tightness factors respectively, where T indicates the relative cramming of a given yarn system taking into consideration the crossovers of the other set of yarns.

β is the ratio of yarn diameters

It is evident that the materials prepared in the "wear" and "water" series provide a fertile field for study of other properties vital to the utility, comfort, and appearance of textile structures. At present, work has been initiated to evaluate the principles of fabric structure which determine dimensional stability under wet and dry conditions, sewability, drape, breaking strength, elongation, bursting strength, air permeability, resistance to water penetration, water absorption, thermal conductivity, tear resistance, and porosity. The results of these studies will be published at frequent intervals as a part of this series of papers on fabric geometry. Some of the papers will deal with extension of the geometrical concepts proposed by Peirce (26) while the reaminder will provide empirical confirmation of the principles developed and furnish detailed data on the fabric properties.

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