MEASURING FABRIC VOLUMETRIC DENSITY UNDER ZERO PRESSURE

قياس الكثافة الحجمية للقماش تحت ضغط صفر

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خلاصة :

يقدم البحث طريقة علمية لقياس الكثافة الحجمية لأى منشا ثلاثى الأبعاد سهل الانثناء كالأقمشة بأنواعها (المنسوج، غير المنسوج، أقمشة التريكو، الخ)، والورق وخلافه. وتكون العينة المختبرة عبارة عن شريحة مستطيلة. ولا يلزم معرفة طول العينة المختبرة، ويتم ضبط عرضها أثناء القص باستخدام ضبعة معروفة العرض. وتعتمد طريقة القياس على العلاقات الرياضية والتفسيرات الفيزيائية بعد تشكيل الشريحة بلفها حول اسطوانات متماثلة تبعا لقاعدة نسيج السادة بحيث تكون الأسطوانات فى مستوى واحد وفى حالة الازدحام النهائى. وتكرر عملية التشكيل لشريحة أخرى من نفس القماش باستخدام عدد مساوى من الأسطوانات ولكن بقطر آخر. ويتم فى كل حالة وزن جزء الشريحة المتداخل مع الأسطوانات (بعد القص). ويقدم البحث صيغة لحساب الكثافة االحجمية للقماش بدقة عالية،كما يقدم فكرة جهاز تم تطويره.

1-Abstract:

In this paper a new scientific method is developed to measure volumetric density of any three-dimensional limp structure such as fabrics whatever their type (woven, non-woven, knitted, etc.), paper, and so on. Material needed for testing must have a perfect rectangular strip shape. There is no need to know how long the tested sample is. There is also no need to measure how wide the tested sample is as width is adjusted using a template. The necessary condition is that these structures are very easy to bend. This method depends on mathematical relations and physical interpretations after shaping (*corrugating*) a fabric strip round light circular straight identical *cylinders* placed in one plane in a jamming situation Fabric shaping is repeated on another part of fabric strip but with another cylinder diameter. This results in a new corrugated fabric weight A formula is derived to obtain fabric volumetric density as a function of fabric strip width, number of cylinders used in every corrugating process, two weights of corrugated fabric and two cylinder diameters. Cylinder diameter must be proportional to both fabric thickness and fabric flexural rigidity. This means that, to make bending and therefore corrugating easier, cylinder diameter must be properly chosen The idea of a new fabric volumetric density meter called *HFDM* is explained

2- Introduction:

It is easy to measure the volumetric density of any homogeneous rigid material by measuring its weight and volume. The case in a fabric or any relatively soft or compressible structure is completely different. It is easy to weigh such structures but it is difficult to measure their volumes as there is a difficulty in measuring their geometrical dimensions such as length, width, and thickness. Length and width can be measured approximately, but thickness is the most difficult dimension to be measured without applying an arbitrarily standardized pressure

Textiles are discontinuous materials produced from macroscopic subelements (finite-length fibres or continuous filaments). This means having void spaces or pores Woven fabrics made from continuous monofilaments have monodisperse pores, whereas woven fabrics manufactured from spun or multifilament yarns have bimodal pore size distributions: pores between yarns and pores within yarn structure. Porosity is one of the important physical quantities used to describe textile materials. Porosity can range widely, depending on product design and processing techniques. The

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closest possible packing of parallel cylinders with uniform radii is in rhombohedral (hexagonal) packing. The porosity of such a system is 0 093. The closest hexagonal packing of spheres with uniform radii would produce a porosity of 0.259. The porosities of real textile materials are surprisingly high reflecting the fact that the component fibres are not densely packed and that fibres are not uniform in shape and thickness. Open and bulky woven and knitted fabrics and certain air-laid nonwovens have porosities in the range of 0.95 and higher. Even those fabrics that appear dense and solid will have porosities in the range of 0.6 to 0.7 [1]. Pore structures of media, particularly fibrous materials, are complex and difficult to quantify. Fibre structure properties and fibre pore structure contribute to liquid transport and retention phenomena in 100 % cotton and polyester fabrics [2]. Statistical analysis of experimental data revealed the effect of yarn type, yarn linear density, and tightness factor of fabric on the linear and areal shrinkage behaviour of silk and cotton knitted fabrics [3].

Measuring dimensions of a solid body could be achieved by using a ruler, a gauge, a planimeter, or by getting use of its physical and chemical properties. The problem in textiles is that boundaries of structure are difficult to be located. Thickness at low pressure is useful in applications for bulk and heat insulation. The relation between pressure and thickness is useful in studying softness of handle and fabric compressibility. Devices based on compression are of doubtful use in measuring thickness because of the interaction of count and twist in determining compressibility. Fabric thickness measurement needs suitable pressing feet, dial gauges, and pressures [4]. Macdonald [5] designed an instrument that could apply pressures as low as 0.001 $lb/in.^2$. Kawabata [6], and Shirley [7] used different fabric thickness meters but their results are highly correlated [8]. CSIRO [8] developed a series of instruments that are inexpensive, robust, and simple to use and their related test methods. This series is called FAST (Fabric Assurance by Simple Testing). FAST-1 gives a direct reading of fabric thickness over a range of loads with micrometer resolution. The FAST-1 compression meter measures fabric thickness over a circular area of 10 cm^2 at a minimum pressure of 2 g/cm^2. De Jong, S., and Tester, D. H. [9] regard a fabric as consisting of an incompressible core and a compressible surface layer. They state that the degree of fabric compression affects the thickness of the fabric surface layer and consequently the appearance and handle.

CSIRO [8] defines very flexible fabrics as those having a weight less than 200 g/m^2 and having therefore low bending rigidity. NING PAN et al. [10] used data on selected fabrics of different fibre types, weave constructions, and fabric thickness to "fingerprint" or characterize fabrics. They state that fullness and softness as well as finish stability are all related to fabric compressional properties. Kawabata [11] measured fabric thickness at 0.5 g/cm^2 and defined fullness and softness as a feeling which comes from bulky, rich and well formed feeling. He stated that springy property in compression and thickness accompanied with warm feeling are closely related with this feeling.

It is not easy to measure fabric thickness as it is neither visually determined nor dimensionally stable. It is also difficult to be calculated because the calculation of fabric thickness depends on fabric volumetric density which depends on fabric structure, and yarn volumetric density. Ebraheem [12] expressed volumetric density of plain square woven fabric as a function of yarn cover ratio and yarn volumetric density. Trials have been made to develop instruments that measure fabric thickness under specific pressures [13]. These pressure values don't distinguish the differences between different fabrics as the same pressure is used for a variety of fabrics.

Yigit [14] developed a computer model to estimate fabric resistance to heat transfer depending on fabric resistance data and fabric thickness data for clothes. McCullough [15] discussed factors affecting insulation and evaporative resistance of cloth. These factors included fabric thickness, fabric density, body surface area covered by garment, evenness of fabric distribution on body, the increase in surface area for heat loss due to clothing, the looseness of tightness of fit, person's body position (sitting or standing), body motion, and wind. McBride [16] studied the microstructure in dry plain weave fabric during large shear deformation in terms of yarn width, yarn spacing and fabric thickness. Fabric thickness is important in fabric pleating process. For successful pleating, firm, stiff fabrics are required. With thick fabrics it is not possible to obtain a sharp pleating angle and fabrics which pleat well usually have a high bending length and low thickness, i.e. high bending modulus [17]. Important properties to investigate fabric handle are stiffness, smoothness, cloth weight, cloth thickness, hardness, and cover factor. It was concluded that it is possible to give a fairly complete description of handling properties in terms of fabric stiffness, smoothness, and thickness [18]. It has been suggested that thickness measurements on the specimens under abrasion resistance test give the rate of wear [19].

Fabric volumetric density may change after use due to yarn or fibre migration. Repeating bending of webbings used as seat belts in cars caused a drop of about 8 % in strength and an increase in webbing thickness of about 3.2 % after 500,000 fatigue cycles, indicating relative movement of fibres and yarns in the fabric. Outside the bending region there was a decrease in thickness of about 2 % [20]. After use, fabric thickness decreases due to yarn flattening. Yarn flattening and fabric extension cause reduction in yarn crimp ratio. Fabric weight per unit area will be decreased [21].

From previous introduction it is clear how fabric volumetric density is important and how its measuring is difficult Fabric volumetric density at low pressure is difficult to be measured but it has many applications In this paper a new strategy is planned. This strategy fulfils achieving four decisions. The first decision is avoiding the problems of minimum pressure. The second is avoiding the problem of presser foot dimensions. The third is avoiding the problem of dial gauges compatibility. The fourth is measuring only one longitudinal dimension (fabric strip width) which is kept constant during the whole test. This strategy depends on fabric strip width measurement, weight measurement, and calculating to measure fabric volumetric density.

3- Theory of Test Method:

If a strip of fabric interlaces with straight cylinders according to the rule of plain weave in such a manner that cylinders reach the jamming state and occupy one plane, then the fabric-cylinders assembly will produce a geometrical model. This model can be analytically defined in terms of fabric thickness, cylinder diameter, and number of cylinders. If

D : cylinder diameter (mm)

N : number of cylinders

t : fabric thickness (mm)

then the length of fabric strip which makes complete interlacing repeats with cylinders can be determined from the following relation:

$$l_t = \frac{\pi N(D+t)}{2} \qquad (1)$$

l_t : length of fabric strip lapping around cylinders (mm)

To express weight of fabric strip lapping around cylinders, two other informations must be used: strip width and fabric weight per unit area. If

b : width of fabric strip (mm)

ω : fabric weight per unit area (mg/mm^2)

then

$$W = l_t b \omega \qquad (2)$$

W : weight of fabric strip lapping around cylinders (mg)

From (1) and (2)

$$\therefore W = \frac{\pi N b \omega (D+t)}{2} \qquad (3)$$

From (3)

$$\therefore t = \frac{2W}{\pi N b \omega} - D \qquad (4)$$

Equation (4) shows that fabric thickness can be expressed in terms of parameters of the foregoing geometrical model besides an intrinsic property of the fabric (fabric weight per unit area). These parameters are cylinder diameter, number of cylinders, strip width, and weight of fabric strip lapping around cylinders. If fabric weight per unit area is not known or if it can not be obtained as accurately as required, another sample of the same fabric with the same width is corrugated with the same number of cylinders but of a different diameter. If new diameter is D', and the weight of the corresponding corrugated fabric is W', the last relation will be

$$t = \frac{2W'}{\pi N b \omega} - D' \qquad (5)$$

From (4) and (5)

$$t = \frac{W'D - WD'}{W - W'} \qquad (6)$$

Also from (4) and (5)

$$\omega = \frac{2}{\pi N b}\left(\frac{W - W'}{D - D'}\right) \qquad (7)$$

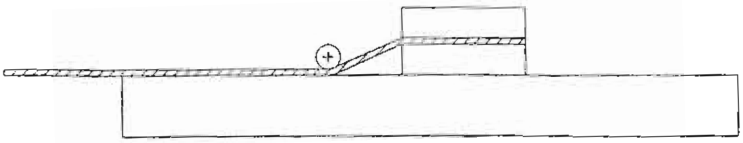
But $\rho_f = \dfrac{\omega}{t}$ (8)

ρ_f : fabric density (mg/mm^3)

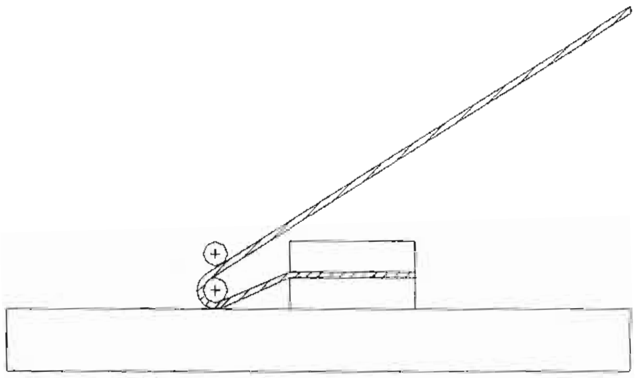
Substituting from (6) and (7) in (8)

$$\therefore \rho_f = \frac{2(W - W')^2}{\pi N b (D - D')(W'D - WD')} \qquad (9)$$

The last equation expresses fabric volumetric density as a function of two weights, two cylinder diameters, number of cylinders used in lapping, and strip width. Fig.(1) shows how cylinders are interlaced with fabric strip.



1-a: Inserting First Cylinder on Fabric Strip



1-b: Inserting Second Cylinder on Fabric Strip

Fig. (1): Interlacing Process

4- Building on Scientific Basis:

Simply, we can say if you want to determine the volumetric density of a fabric without going into problems of suitable pressure, suitable presser foot diameter, or dial gauge accuracy and without needing to know fabric weight per unit area, please corrugate a rectangular strip of this fabric by lapping it around identical cylinders of suitable diameter according to the rule of plain weave. This means that lapping must be in an alternative manner. It is also required that cylinders lie in one plane and reach the jamming state. This makes lap angle around each cylinder equal to $180°$. It is then required to remove fabric outside the lapping zone. This needs cutting the fabric protruding outside this zone The last procedure is repeated with another sample of the same fabric with changing only wire diameter. Data obtained from this test are strip width, number of cylinders used in lapping, two cylinder diameters, and two lapped strip weights. With these data it can be substituted in equation (9) to get a reading of fabric volumetric density

5- Developing a New Fabric Volumetric Density Meter:

A small device equipped with groups of circular light rigid straight cylinders of different diameters is built. Cylinders may be made hollow if possible. Cylinder diameters are 4, 5, 6, 8, 10, and 12 mm to be suitable for fine and coarse fabrics. The device consists of two slotted straight bars connected by a back plate to give a working distance of 63 mm between the two slots which are facing each other. The two ends of each cylinder are made cylindrical with a radius of clearance with the slot width (4 mm) and a length equal to the slot depth. This clearance facilitates inserting cylinders one after the other during fabric strip corrugating. A base plate 61 mm wide is mounted to the back plate Two fabric strip clamps of length 80 mm are also needed. The instrument must be equipped with more similar clamps to facilitate preparing more than one fabric strip from the same fabric. The bar frame occupies a space of about 500 mm * 100 mm * 52 mm. The height of the device depends on the class of fabrics tested (thin, medium, or thick). The bar frame can be tilted and fixed at a suitable angle with vertical to facilitate the corrugating process. A digital electronic balance which measures to the nearest 0 1 milligram is suitable for weighing corrugated fabric sample. A sketch of the device is shown below.

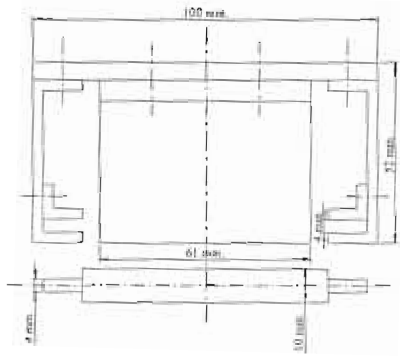


Fig. (2): A sketch of the device (a plan view) indicating the two vertical 4-mm slots, the 61-mm wide base plate, and one 10-mm diameter cylinder drawn separately

6- Test Procedure:

6-1- Preparing Fabric Specimen:

A strip of fabric is cut in a rectangular form with a sufficient length and a suitable width for corrugating (lapping process). This is carried out using a template (60 mm width) and a sharp cutter.

6-2- Lapping:

Fabric strip is clamped by two pairs of clamps in its two extremities. One pair of clamps is fixed to the base plate of the device. The other clamp is gripped by a hand and a cylinder is inserted gently by the other hand through the two slots till it reaches the fixed clamp. The first hand is moved (with clamp) to the other side of the bar frame to cover the previous cylinder and another cylinder is inserted by the other hand. This procedure is repeated till a considerable length of fabric is lapped around a suitable number of cylinders.

6-3- Cutting:

Strip parts outside lapping zone are removed by cutting it using the sharp cutter at two corresponding points. one just before the first cylinder, and one just after the last cylinder in such a manner that complete lapping repeats are obtained

6-4- Weighing:

Corrugated fabric strip is accurately weighed.

6-5- Repeating the Test:

The previous steps are repeated with another part of the fabric changing only cylinder diameter.

6-6- Tabulating Data:

Data obtained from repeated lapping and weighing are put in a table to be used in calculations. In the title of the table, atmospheric conditions with respect to temperature and relative humidity are mentioned.

6-7- Calculating:

Fabric volumetric density is determined by substituting for the test data in equation (9). With every pair of measurements, a value of fabric volumetric density is calculated.

7- Data Obtained From The Test:

Data obtained from this test are fabric strip width, number of cylinders used in corrugation, first weight of corrugated fabric strip W, first cylinder diameter D, second weight of corrugated fabric strip W', and second cylinder diameter D'

8- Determining Fabric Volumetric Density:

Substituting for data obtained from the test in equation (9) one reading of fabric volumetric density is determined

9- Number of Fabric Volumetric Density Readings:

If test procedure is carried out m times with m different cylinder diameters, then m different weight values of corrugated fabric are obtained. Making computations of 2 among these m results, a number of fabric volumetric density readings n is obtained. The relation between number of fabric volumetric density readings and number of samples is as follows:

$$n={}^{m}C_2 = \frac{m(m-1)}{2} \qquad (10)$$

m : number of fabric samples lapped or number of cylinder sets used.

n : number of fabric volumetric density readings.

It is clear from equation (10) that beginning from 4 cylinder sets, number of thickness readings will be more than number of test specimens. This is indicated in Table (1).

Table (1): Number of Fabric Volumetric Density Readings (n) Obtained from Lapping and Weighing Procedures (m)

m	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
n	0	1	3	6	10	15	21	28	36	45	55	66	78	91	105
m	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
n	120	136	153	171	190	210	231	253	276	300	325	351	378	406	435

10- Statistical Data of Fabric Volumetric Density:

Fabric volumetric density readings are statistically analysed to get means such as arithmetic mean and measures of dispersion such as coefficient of variation.

11- Philosophy Behind Test Method:

The philosophy behind this new method for fabric volumetric density measurement is that it is dealt mathematically with neutral plane of the fabric. Length of fabric neutral plane is not affected by fabric flattening if it occurred. Fabric flattening occurs in a neighbourhood of fabric napping point between cylinders This results in a slight local change in fabric configuration around every cylinder but there will be no fabric migration from one cylinder to the next depending on fabric flexibility. Therefore, the effect of flattening or compressibility will not be translated to corrugated fabric length. In this test method no fabric dimensions are needed except for strip width. Strip width is adjusted using the template. Generating a great number of test results from a small number of test procedures helps obtain a high degree of accuracy inspite of reducing the amount of fabric used. Calculating allows obtaining density as accurate as required (e.g. to the nearest 0 0001 g/cm^3).

12- Verification:

To verify the applicability of this test method, two fabrics which are very poor in regularity were tested.

12.1. First Fabric:

12.1.1. At a temperature of 24 °C and a relative humidity of 68 %, eight samples were tested. Number of cylinders used for lapping were 34. Two cylinder diameters were chosen: 4 mm and 10 mm.

At 4-mm diameter weights of corrugated samples in mg were:

2744.8 2756.6 2836.5 2799 6 2961.2 2828 1 2684.9 2732.3

Average weight = 2793 mg Coefficient of variation = 3.04 %

At 10-mm diameter weights of corrugated samples in mg were:

6383.5 6700.9 6546.8 6414.8 6857 5 6813.6 6501.6 6449 9

Average weight = 6583.5 mg Coefficient of variation = 2.7899 %

Fabric Volumetric Density obtained from Equation (9) = 0.468229 mg/mm^3 (or 0.47 g/cm^3).

12.1.2. At a temperature of 22 °C and a relative humidity of 62 %, eight samples were tested Number of cylinders used for lapping were 34 Two cylinder diameters were chosen 4 mm and 10 mm.

At 4-mm diameter weights of corrugated samples in mg were:

2747.8 2752.5 2796 9 2761 6 2957.0 2721 9 2806.4 2683.1

Average weight = 2778 4 mg Coefficient of variation = 2.9551 %

At 10-mm diameter weights of corrugated samples in mg were.

6421.5 6687.3 6556.7 6436 2 6812.8 6800.0 6490.0 6333.3

Average weight = 6567.2 mg Coefficient of variation = 2.7788 %

Fabric Volumetric Density obtained from Equation (9) = 0.49249 mg/mm^3 (or 0.49 g/cm^3).

12.1.3. If readings in 12.1.1. and 12.1.2. were at the same atmospheric conditions, then 16 readings would be obtained and

At 4-mm diameter

Average weight = 2785.7 mg Coefficient of variation = 2.9092 %

At 10-mm diameter

Average weight = 6575.4 mg Coefficient of variation = 2.6787 %

Fabric Volumetric Density obtained from Equation (9) = 0.4802 mg/mm^3 (or 0.48 g/cm^3).

12.2. Second Fabric:

12.2.1. At a temperature of 22 °C and a relative humidity of 62 %, ten samples were tested. Number of cylinders used for lapping were 30. Two cylinder diameters were chosen: 5 mm and 10 mm.

At 5-mm diameter weights of corrugated samples in mg were:

1471.5 1411.1 1444.3 1366.3 1458.5 1438.8 1321.3 1480.4
1432.7 1436.8

Average weight = 1426.2 mg Coefficient of variation = 3.4266 %

At 10-mm diameter weights of corrugated samples in mg were:

2666.2 2928.6 2996.4 2969.0 3038.1 3006.0 2974.7 2906.0
2732.1 2867.1

Average weight = 2908.5 mg Coefficient of variation = 4.1981 %

Fabric Volumetric Density obtained from Equation (9) = 0.554182 mg/mm^3 (or 0.55 g/cm^3).

12.2.2. At a temperature of 22 °C and a relative humidity of 62 %, other ten samples were tested. Number of cylinders used for lapping were 30. Two cylinder diameters were chosen: 5 mm and 10 mm.

At 5-mm diameter weights of corrugated samples in mg were:

1467.6 1407.0 1440.3 1361.6 1455.0 1434.8 1323.8 1470.8
1428.7 1435.6

Average weight = 1422.5 mg Coefficient of variation = 3.2966 %

At 10-mm diameter weights of corrugated samples in mg were:

2921.0 2986.3 2960.4 3031.7 2996.6 2964.4 2899.0 2724.4
2856.5 2664.1

Average weight = 2900.4 mg Coefficient of variation = 4.1554 %

Fabric Volumetric Density obtained from Equation (9) = 0.55776 mg/mm^3 (or 0.56 g/cm^3)

12.2.3 At a temperature of 22 °C and a relative humidity of 62 %, twenty samples were tested. Number of cylinders used for lapping were 30. Two cylinder diameters were chosen: 5 mm and 10 mm.

At 5-mm diameter weights of corrugated samples in mg were:

1471.5 1411.1 1444.3 1366.3 1458.5 1438.8 1321.3 1480.4
1432.7 1436.8 1467.6 1407.0 1440.3 1361.6 1455.0 1434.8
1323.8 1470.8 1428.7 1435.6

Average weight = 1425.6 mg Coefficient of variation = 3.3711 %

At 10-mm diameter weights of corrugated samples in mg were:

2666.2 2928.6 2996.4 2969.0 3038.1 3006.0 2974.7 2906.0
2732.1 2867.1 2921.0 2986.3 2960.4 3031.7 2996.6 2964.4
2899.0 2724.4 2856.5 2664.1

Average weight = 2904.4 mg Coefficient of variation = 4.0668 %

Fabric Volumetric Density obtained from Equation (9) = 0.5815336 mg/mm^3 (or 0.58 g/cm^3).

13- Conclusion:

By this test method real fabric volumetric density can be determined. This method can be used to test any flexible 3-dimensional structure irrespective of whether it is a fabric (woven, non-woven, knitted, etc.) or another material like paper etc. The influence of fabric softness on volumetric density measurement could be avoided by the developed test method. Variability of weight readings and consequently in density values is attributed to fabric irregularity. For regular fabrics, it is expected that results will be more uniform.

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