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Modelling Surface Roughness of 3/1 Twill Fabric Using Weft Yarn Count and Weft Thread Density

Modeliranje površinske hrapavosti tkanine v vezavi keper 3/1 na podlagi dolžinske mase votka in gostote niti v smeri votka

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Abstract

The surface roughness of fabric is one of the fabric properties that is used to evaluate the sensorial comfort of clothes. However, its objective evaluation requires sophisticated and expensive testing instruments and skilled testing expertise. Developing a predictive model is therefore an alternative approach to overcome such limitations. This study investigated a regression model to predict the surface roughness of 3/1 twill fabric using weft yarn count and weft thread density. Nine samples were produced by varying the weft yarn count and weft thread density at three different levels, while their surface roughness was determined using a Kawabata instrument (KES-FB4) under standard testing conditions. A two-factor predictive model equation was developed using design expert software. Based on the results and findings, the effects of count and density on the roughness of 3/1 twill fabric were found to be statistically significant for the developed model at a confidence interval of 95%. The model was tested by correlating the measured and predicted surface roughness values of 100% cotton 3/1 twill fabric. The results of the model test indicate a significant correlation ($R^2 = 0.9644$) between the measured and predicted surface roughness values of 3/1 twill fabric, with a 95% confidence interval.

Model validation was performed, and the study showed that the measured and predicted values of the surface roughness of 3/1 twill fabric have a 0.828 coefficient of determination (R^2). This indicates that the surface roughness of 3/1 twill fabric can be predicted well by weft yarn count and weft thread density. This model can be thus used in textile industries and by research institutes for predicting the surface roughness of 3/1 twill fabrics in the new product development process.

Keywords: surface roughness, 3/1 twill weave, weft yarn count, weft thread density, predictive model

Izvleček

Površinska hrapavost tkanine je ena od lastnosti tkanine, ki se uporablja za oceno čutnega udobja oblačil. Objektivno vrednotenje čutne udobnosti zahteva sofisticirano in drago laboratorijsko opremo in ustrezno usposobljenost za izvedbo ekspertize. Razvoj napovednega modela je alternativni pristop za premagovanje omenjenih omejitev.

V tej študiji je bil raziskan regresijski model za napovedovanje površinske hrapavosti tkanine v vezavi keper 3/1, ki temelji na dolžinski masi votkovnih niti in gostoti niti v smeri votka. Izdelanih je bilo devet vzorcev, pri katerih so spreminjali dolžinsko maso votka in gostoto votkovnih niti na treh različnih ravneh, pri čemer je bila površinska hrapavost tkanin določena z instrumentom Kawabata (KES-FB4) v standardnih razmerah preizkušanja. S pomočjo programske opreme Design Expert je bila razvita enačba dvofaktorskega napovednega modela. Na podlagi rezultatov je bilo ugotovljeno, da je vpliv dolžinske mase votka in gostote votkovnih niti na hrapavost tkanine v vezavi keper 3/1 pri razvitem modelu statistično značilen pri 95-odstotnem intervalu zaupanja. Model je bil preverjen s pomočjo korelacije izmerjenih in predvidenih vrednosti površinske hrapavosti 100-odstotne bombažne tkanine v vezavi keper 3/1, pri čemer je bila ugotovljena visoka korelacija (r^2 = 0,9644) med izmerjenimi in predvidenimi vrednostmi. Izvedena je bila validacija modela, ki je pokazala, da imajo izmerjene in predvidene vrednosti površinske hrapavosti tkanine v vezavi keper 3/1 koeficient validacije (R^2) 0,828. To kaže, da je s podatki o dolžinski masi votka in gostoti votkovnih niti mogoče dobro napovedati površinsko hrapavost tkanine v vezavi keper 3/1. Zato je model primeren za napovedovanje površinske hrapavosti tkanin v vezavi keper pri razvoju novih izdelkov v tekstilni industriji in na raziskovalnih inštitutih.

Ključne besede: površinska hrapavost, vezava keper 3/1, dolžinska masa votkovnih niti, gostota votkovnih niti, napovedni model

1 Introduction

A consumer's sensations and experiences are used to assess fabric comfort, which is a full physiological, psychological and physical assessment of a fabric and its surroundings [1–3]. The sensorial comfort of clothing has a great impact on customer choice and satisfaction. The sensorial comfort of clothing is determined by the sense of touch of fabric properties, such as surface state, weight, thickness, shear, compression, bending and tactile factors [4]. The surface roughness of textile fabric is one of the most important fabric parameters influencing fabric handle and customer preferences because of its effect on wellbeing, and the performance and efficiency of garments [5, 6]. Surface roughness is a tactile fabric property that is an important part of skin sensorial wear comfort, which describes the mechanical contact sensations caused by a textile on the skin [7, 8]. Surface roughness and other low-stress mechanical properties include softness, drapeability and the comfort of cloth in relation to the handle properties thereof [8]. The surface of woven fabrics is not flat and smooth because fabrics are produced through the interlacement of warp and weft yarns with irregularities. Thus, due to the interlacement of warp and weft yarns and the inherent non-uniform structure of spun yarns, the geometrical roughness of a fabric is, to a certain extent, considerable [9].

Therefore, evaluating the surface roughness of clothing is important for both manufacturers and wearers. The surface roughness of the fabric can be assessed subjectively or using an objective measurement system with different testing equipment, such as the Kawabata evaluation system, FAST and other tough senor instruments [10–13]. The subjective evaluation of fabric handle requires a highly skilled person, while the results vary from person to person and over time. However, it is simple and can be applied anywhere, without any limitation. Due to a lack of quantitative descriptions and poor data comparability, the application of the subjective assessment of fabric handle is limited [14]. Such limitations result in the development of highly sophisticated and accurate instruments to quantify fabric handle properties. The objective measurement of fabric handle properties was started by Peirce. Many researchers subsequently investigated the development of instruments for the objective measurement of fabric handle properties [15, 16]. The Kawabata Evaluation

System (KES-F) and Fabric Assurance by Simple Testing (FAST) system were the two commonly used instruments for determining the handle properties of fabric [17, 18].

As described above, the hand feeling of the fabric is a combined effect of several characteristics. Among these, surface roughness is the basic and critical factor for clothing [17]. The surface roughness of fabric can be quantified using a surface profile system called surface height variation (SHV), applying two methods: contact/mechanical or non-contact methods. This study focused on the evaluation of surface roughness using the contact or mechanical method [17]. It is known that determining the surface roughness of fabric requires well-organized laboratories, including skilled experts, different consumable materials, expensive testing machines (like KES and FAST) and other facilities, such as air conditioning systems. Because of the large investment and running cost for determining the surface roughness of fabric using expensive instruments, clothing industries cannot test surface roughness and other related fabric properties. Today, however, researchers investigate other means, such as mathematical modelling, statistical tools and computer applications to predict fabric properties based on constructional and material parameters [18, 19]. Taieb, Mshali [20] used an artificial neuro network (ANN) to predict fabric drapability based on fabric formability resulting from the FAST system. Other researchers [21] predicted the bending rigidity and shear stiffness of fabric based on a three-dimensional model. Similarly, the water absorption properties of polyurethane and acrylic binder-treated polyester fabric were predicted using an adaptive neuro-fuzzy inference system (ANFIS) and artificial neural network (ANN) methods [22]. Researchers also developed predictive models for the surface roughness of fabrics and other materials. For example, the surface roughness of free-hand grinding was predicted using a regression modal based on the parameters of machine vision [19], while the surface roughness of woven fabric was modelled based on weave structure and weft density [23]. A regression model was developed to predict the surface roughness of woven bed sheet fabric based on weft count and weft thread density [24]. The development of predictive models for the evaluation of the surface roughness of fabric helps to avoid existing trial and error in the product development process. To develop a predictive model, all factors affecting the surface roughness of a fabric should be investigated and analysed. There are a number of factors that influence the surface roughness of woven fabric. They are mainly fibre type [25], fibre properties (fineness, length and strength) [26], yarn properties and fabric properties [27, 28]. Fabrics made of fibres with high bending rigidity and tensile resilience (such as linen) show low shear rigidity, while shear hysteresis is stiffer and demonstrates a higher surface roughness. On the other hand, fabrics made from fibres with low bending rigidity, such as 100% cotton and cotton/viscose, have a soft and smooth surface [29]. Fibre properties, such as fineness, length and bending stiffness, affect the surface properties of fabric. Coarser fibres have a higher bending rigidity, while the yarns and fabrics made of such types of fibres are stiffer and have a harsh feeling. The surface friction of yarn and fabric are affected by the length and length uniformity of the constituent fibres. For example, 100% cotton fabric and hairiness on the fabric surface, which is mainly influenced by fibre length and length uniformity, plays an important role in terms of the surface roughness of fabric [30]. Yarn properties, such as twist level, bulkiness, uniformity and flexibility/stiffness, affect the surface roughness of fabrics. Fabrics made of high twisted and stiffer yarns have a higher bending rigidity, which results in the higher surface friction of fabrics. Yarn with higher unevenness and a larger number of irregularities increase the surface friction of fabrics made from such types of yarns. Fabric properties are the cumulative effect of fibre type, fibre properties, yarn properties and fabric constructional parameters. Thus, any factor that affects the hairiness, tensile, bending, shearing, compression and thickness of the fabric affects fabric surface roughness.

Researchers have found that the surface roughness of woven fabric decreases in the warp, weft, and diagonal direction when the weft yarn density increases [31, 32]. However, many researchers have not studied which type of regression model equation has better a predictive and evaluation ability when quantifying this property spatially for 3/1 twill fabric, or and how to evaluate and identify the accuracy, reliability and rationality of the model equations. Hence, it is intended to develop a linear equation based on weft yarn count and weft thread density for studying the surface roughness of 3/1 twill fabric. This study focused on the development of a novel predicted regression model for the surface roughness of 3/1 twill fabric based on the weft yarn count and weft thread density.

2 Materials and methods

Cotton woven fabrics with different weft yarn count and weft thread density were used to determine surface roughness. Fabrics were made of 100% cotton ring spun warp yarn and open end (OE) rotor-spun weft yarn, while the detailed fibre properties used to produce weft yarns were evaluated using USTER HVI 1000, as shown in Table 1: Cotton fibre properties.

Table 1: Cotton fibre properties

Fibre	Cotton
Spinning consistency index, SCI	106.7
Moisture content (%)	4.85
Micronaire index (-)	4.735
Maturity (-)	0.87
Upper half mean length, UHML (mm)	28.42
Short fibre (%)	9.45
Strength (g/tex)	22.38
Elongation (%)	6.86

Nine 3/1 twill woven fabrics were produced at the Kombolcha Textile Share Company (KTSC) by varying the weft yarn count and weft thread density, as shown in Table 2, while other fabric constructional parameters, such as warp density, warp count, tension, speed, RH% and machine speed (rpm) remained unchanged for all samples (see Table 2). The weft yarn count and weft thread density (only for the model test) were determined according to the ISO 2060:1994(R2019) and ISO 7211-2 standards, [33, 34] respectively, under standard atmospheric testing conditions.

Table 2: Sample fabric construction parameters (3/1 twill fabric)

Fabric sample no.	Warp thread density (cm^{-1})	Warp yarn count (tex)	Weft thread density (cm^{-1})	Weft yarn count (tex)
S1	24	30	18	20
S2	24	30	18	30
S3	24	30	18	42
S4	24	30	22	20
S5	24	30	22	30
S6	24	30	22	42
S7	24	30	26	20
S8	24	30	26	30
S9	24	30	26	42

Combined pretreatment was conducted for all samples using 3% sodium hydroxide, 4% hydrogen peroxide, 2% sodium silicate, 0.5% wetting agent and 0.5 ethylenediaminetetraacetic acid (EDTA) on the weight of fabric with a liquor ratio of 1:20. The sample fabrics were dried using a hot air oven at 50 °C for 15 minutes. After the pretreatment process, the surface roughness mean deviation (SMD) of the fabrics was determined using the Kawabata evaluation system under standard atmospheric conditions.

The Kawabata evaluation system (KES-FB4) can simultaneously measure a fabric's geometrical roughness and the coefficient of friction (µm) using a sensing element comprising a metallic rod equipped in its free end with a thin U-shaped wire. The sensor touched the surface of the fabric under a constant normal force and the vertical movement of the sensor due to the fabric surface roughness that proportionally transformed to an electrical signal [9, 24, 32].

The experimental condition was determined by three-level factorials using the Design Expert @11 software. This means that each independent factor, i.e. the weft yarn count (tex) and weft thread density (picks/cm), changed at three different values, as shown in Table 2. The experiment had nine non-centre and four centre points, and a total of 13 runs with five numbers of replications, as shown in the Table. 3.

Table 3: Experimental design with two factors and three levels

Fabric sample code	Run	Factor 1	Factor 2	Response SMD (μm)
		A: weft yarn count (tex)	B: weft thread density (cm^{-1})	
S2	1	20	22	1.69
S5	2	30	22	2.01
S8	3	42	22	2.85
S1	4	20	18	1.81
S6	5	30	26	1.94
S5	6	30	22	2.01
S4	7	30	18	2.50
S7	8	42	18	3.45
S5	9	30	22	2.01
S5	10	30	22	2.01
S9	11	42	26	2.00
S5	12	30	22	2.01
S3	13	20	26	1.56

A predictive model for the surface roughness of 3/1 twill fabric was developed in terms of actual and coded units by a design expert. To arrive at the actual equation, each term in the coded equation was replaced with its coding formula (equation 1).

$$X_{coded} = \frac{X_{actual} - \bar{X}}{(X_{High} - X_{Low})/2} \qquad (1)$$

where X_{coded} represents the coded values of surface roughness, X_{actual} represents the actual surface roughness, $\bar{X}$ represents the mean values of a surface roughness, X_{High} represents the maximum values of surface roughness and X_{Low} represents the minimum value of surface roughness.

The surface roughness of 3/1 twill fabric was predicted based on a general two-factor predictive model (equation 2), while the model was validated using the actual measured and predicted values of the surface roughness of 3/1 twill fabric.

$$SMD = \beta_0 + \beta_1 x + \beta_2 y + \beta_3 x \times y \qquad (2)$$

where *SMD* represents the surface roughness (μm), *x* represents weft yarn count (tex), and *y* represents weft thread density (cm^{-1}).

3 Results and discussion

3.1 Development of a predictive model for the surface roughness of 3/1 twill fabric

A predictive model for the surface roughness of 100% cotton 3/1 twill pretreated fabric was developed using the measured surface roughness values of nine samples, which were measured using a KES-FB4 instrument. An equation for the surface roughness (equation 3) was developed based on two independent variables or factors (weft yarn count and weft thread density) with three different levels of each. This equation should not be used to determine the relative impact of each factor because the coefficients are scaled to accommodate the units of each factor and the intercept is not at the centre of the design space.

$$SMD = -1.85024 + 0.201288x + 0.112974y - 0.00689xy \qquad (2)$$

where *SMD* represents the surface roughness (μm), *x* represents weft yarn count (tex), and *y* represents weft thread density (cm^{-1}).

The effect of the two factors – weft thread density and weft yarn count – on the surface roughness of 3/1 twill fabric is described in Table 3. As is evident from Table 3, three samples (S2, S5 and S8) have the same fabric constructional parameters, except the weft yarn count. S2, S5 and S8 were produced from 20 tex, 30 tex and 42 tex weft yarns, respectively, and the measured surface roughness values of these samples were 1.69 µm, 2.01 µm and 2.85 µm, respectively. S2 had the lowest surface roughness, while S8 had the highest surface roughness. This difference occurs only due to weft yarn count. A finer weft count has a lower yarn diameter, while the up-and-down movement of the surface sensor in the KES-FB4 instrument is lower. Since an electrical signal occurred due to the vertical reciprocating movement of the sensor, proportionally converted to the surface roughness values of the fabric, the lower vertical movement of the fabric results in lower surface roughness values. Similarly, fabrics made from coarser weft yarn count have a higher amplitude in the reciprocating movement of the sensor, which results in a higher surface roughness value.

Sample fabrics S1, S2 and S3 were produced with 18 cm^{-1}, 22 cm^{-1} and 26 cm^{-1}, respectively, by maintaining other fabric constructional parameters constant. The measured surface roughness values of these sample fabrics were 1.81 µm, 1.69 µm and 1.56 **µm** for S1, S2 and S3, respectively. This result shows that the values of surface roughness decrease as the weft thread density increases. When a fabric is constructed with dense weft thread density, the amplitude of the vertical reciprocating movement of the measuring sensor in the KES-FB4 instrument is low, which results in a low surface roughness value for the fabric.

Table 4 shows the measured and predicted surface roughness values of 3/1 twill fabrics constructed with different weft thread density and weft yarn count. The result shows that weft thread density has a negative correlation and weft yarn count has a positive correlation with the predicted and measured surface roughness values of 3/1 twill fabric.

3.2 Model validity test

To check the validity of the developed model, it was necessary to determine the correlation between the surface roughness of the samples determined using a Kawabata instrument (KES-FB4) and the predicted surface roughness values of the same samples (Table 4). As is evident from Figure 1, the coefficient of determination (R^2) between measured and predicted surface roughness values is 0.96443 at a 95% confidence level. This shows that the predicted and measured surface roughness of 3/1 twill fabric have a strong positive relationship.

Table 4: Measured (SMD) and estimated (SMD) values for model validity for 3/1 twill fabrics

Sample code	Warp density (cm^{-1})	Warp count (tex)	Weft density (cm^{-1})	Weft count (tex)	Measured (SMD)	Estimated (SMD)
S1	24	30	18	20	1.81	1.67
S2	24	30	22	20	1.69	1.60
S3	24	30	26	20	1.65	1.52
S4	24	30	18	30	2.5	2.52
S5	24	30	22	30	2.01	2.14
S6	24	30	26	30	1.94	1.76
S7	24	30	18	42	3.45	3.36
S8	24	30	22	42	2.85	2.68
S9	24	30	26	42	2.00	2.01

In addition, mean comparison was performed at a 95% confidence level to analyse whether there is significant difference between the measured and predicted surface roughness values of 3/1 twill fabric. As is evident from Table 5, the p-value for comparison of means using two sample T-tests is 0.807 at a 95% confidence level, which is much higher than a 0.05 level of significance. That means the predicted and measured surface roughness (SMD) values had no significant difference at a 95% confidence level.

Table 5: Mean comparison for measured and predicted surface roughness values using a two-samples T-test

Properties	**Measured SMD**	**Estimated SMD**	**Difference**	**Hypothesized difference**
Mean	2.211	2.14	0.071	0
Variance	0.367	0.373		
Observations	9	9		

Degree of freedom = 16; t-stat = 0.248; $P(T \leq t)$ two-tail = 0.807; t-critical two-tail = 2.12

Thus, predicting the surface roughness of 3/1 twill fabric using a regression model has a significant impact on the product development process of textile industries and researchers, while it can also help to avoid the purchase of expensive testing instruments, and reduce material destruction during testing and product delivery time.

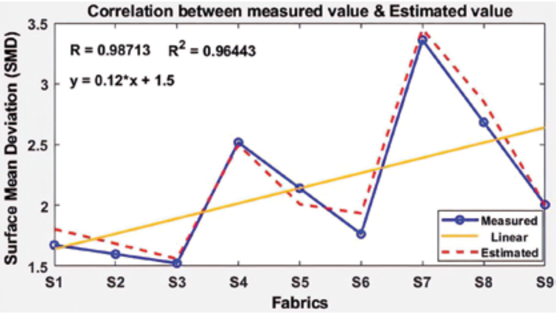

Figure 1: Correlation between SMD values measured using a KES-FB4 instrument and SMD values calculated using a model equation

3.3 Model test

To test the efficiency of the developed model, other three 3/1 twill fabrics were used. The constructions of those fabrics are shown in Table 6. The surface roughness of the three 3/1 twill half-bleached fabrics were determined using a Kawabata instrument (KES-FB4) and predicted using a predictive model.

Table 6: Samples for model test

Sample code	Weave type	Warp density (cm^{-1})	Warp count (tex)	Weft density (cm^{-1})	Weft count (tex)	Measured SMD (µm)	Calculated SMD (µm)
ST_1	Twill 3/1	39	21	22	21	1.59	1.70
ST_2	Twill 3/1	42	29	24	29	2.05	1.92
ST_3	Twill 3/1	38	31	19	31	2.30	2.49

As is evident from Figure 2, the predicted and measured surface roughness value of 3/1 twill fabric have a strong positive relation, while their coefficient of determination (R^2) is 0.8281 at a 95% confidence level.

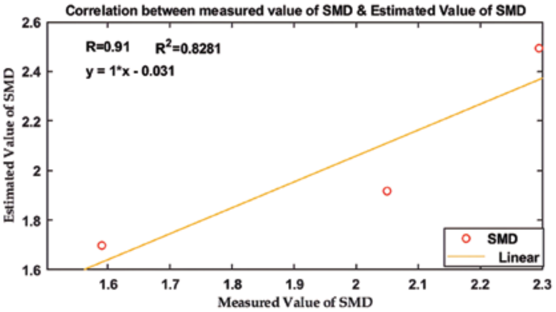

Figure 2: Correlation between SMD values measured using a KES-FB4 instrument and SMD values calculated using a model equation for model testing fabrics

4 Conclusion

This study investigated a regression model for predicting the surface roughness of 3/1 twill fabric based on the weft yarn count and weft thread density. This model was developed based on the surface roughness of the samples measured using a KES-FB4 instrument, while the weft density and weft linear density and the efficiency of the developed model were also verified using the measured and predicted surface roughness values of three 3/1 twill fabrics with different weft counts and weft density. The measured and predicted surface roughness values of 3/1 twill fabric have a strong positive correlation with a 0.828 coefficient of determination(R^2) at a 95% confidence level. Thus, the model can be used in textile industries and research institutes to predict the surface roughness of 3/1 twill fabric in new product development process.

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