THE COMFORT PROPERTIES, MEASURED WITH A SWEATING MANIKIN (WALTER^{TM}), OF CLOTHING ENSEMBLES COMPRISING SUITS OF DIFFERENT FABRIC CONSTRUCTIONS AND FIBRE BLENDS

Anton F Botha*, Lawrance Hunter & Lizaan Britz

ABSTRACT

The main objective of the present study was to determine the relative role and importance of worsted suiting fabric fibre blend, vis-à-vis certain fabric structural parameters, on the comfort related properties of 12 clothing ensembles, each comprising a different man's suit, but the same wool/nylon underwear and cotton shirt. To achieve the objective, the comfort related properties, namely thermal (R_t) and water vapour resistance (R_{et}) and water vapour permeability index (I_m), of the clothing ensembles, as determined by means of Walter^{TM}, a thermal sweating fabric manikin, were subjected to multi-linear and multi-quadratic analysis, as dependent variables, with the various suiting fabric parameters, namely weight, thickness, density, porosity, air permeability and wool content, as independent variables. Only the multi-quadratic regression analysis results have been reported since these best explained the observed differences in the clothing ensemble comfort related properties, in terms of the differences in suiting fabric properties. In general, it was found that variations in suiting fabric air permeability explained more of the variations in the clothing ensemble thermal and water vapour resistance, than did the other suiting parameters investigated, such as fibre blend and fabric weight and thickness. An increase in suiting fabric air permeability was generally associated with a decrease in both the thermal (R_t) and water vapour (R_{et}) resistances of the clothing ensemble, and with an increase in the water vapour permeability index (I_m) of the clothing ensemble.

— ***Dr AF Botha****
CSIR Materials & Manufacturing Operating Unit
PO Box 1124
Port Elizabeth
6000
South Africa
Tel: +27 (0)41 508 3200
Fax: +27 (0)41 508 3277
E mail: afbotha@csir.co.za/
afbothape@gmail.com
*Corresponding author

— ***Prof L Hunter***
[1)]Nelson Mandela University
PO Box 77000
Port Elizabeth
6031
South Africa
[2)]CSIR Materials & Manufacturing Operating Unit
PO Box 1124
Port Elizabeth
6000
South Africa
Tel: +27 (0)41 508 3260
Fax: +27 (0)41 508 3277
E mail: lawrance.hunter@nmmu.ac.za

— ***Ms L Britz***
Nelson Mandela University
PO Box 7700
Port Elizabeth
6031
South Africa
Cell: +27 (0)76 315 4218
E mail: lizaanbritz8@gmail.com

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INTRODUCTION

Both the consumers and the clothing industry are increasingly focussing on the comfort of clothing. Comfort is a multidimensional concept (Li, 2001), with various influencing factors. Nevertheless, certain key aspects can be highlighted, such as physical comfort (effects of external environment), psychological comfort (the mind's ability to keep functioning effectively without external help) and physiological comfort (including the body's ability to maintain life), all of which have a significant influence on the wearer (Fan and Hunter, 2009; Stoffberg *et al.*, 2015). Various detailed reviews on comfort and the factors which affect it are available for a broad and better understanding of the various concepts involved (Ukponmwan, 1993; Li, 2001; Laing and Sleivert, 2002). The thermal comfort of a human being depends on a variety of factors, such as the external climatic conditions, physical activity and the combination of clothing worn (Li, 2001). Air entrapment mainly influence fabric and clothing thermal comfort, it in turn being influenced by various fabric and clothing structural parameters, such as fabric thickness and pore size distribution and cross-section diameter, number of fabric layers and clothing design and fit (Li, 2001; Barker, 2008). The body's thermoregulatory responses are highly sensitive to the water vapour permeability of clothing, as even partially impermeable clothing can decrease heat tolerance significantly, due to constant sweat production, without the fabric allowing the perspiration to pass through. Thus a steady state is not possible, because heat generation may be greater than heat loss under these conditions (Fan, 2006). Properties, such as thermal resistance, water vapour resistance, air permeability and liquid water permeability, are key in terms of the thermal comfort of the human body (Das et al., 2007; Bedek et al., 2011). The movement of moisture through fabrics can be influenced by a number of factors, including yarn twist, fabric structure (especially porosity and permeability), garment construction, fabric treatment/finishing applied and fibre properties (Fan and Hunter, 2009).

Among other things (e.g. protection, fashion, culture, status, etc.), clothing serves as a barrier between the body and the environment, acting as a "second skin" to the human being (Mukhopadhyay and Midha, 2008a; Tyagi *et al.*, 2009; Voelker et al., 2009; Manshahia and Das, 2014). Clothing essentially acts as a buffer to the free exchange of heat, between the body and the external environment. Thus, the most important aspect of thermal insulation is protecting the human body from unpleasant or extreme external cold or hot conditions (Ukponmwan, 1993). A crucial function of clothing is to protect the body from external climatic conditions, to ensure thermal comfort and prevent the body's core temperature from dropping too low, which could result in a life threatening situation (Fan and Chen, 2002; Mukhopadhyay and Midha, 2008a; Fan and Hunter, 2009; Voelker *et al.*, 2009; Stoffberg *et al.*, 2015. The wear comfort of clothing is largely affected by the heat transfer from the body through the clothing ensemble. When a person takes part in a physical activity, or any metabolic activity, heat is generated throughout the body (Matusiak, 2010; Bhatia and Malhotra, 2016). In order for the body to maintain a state of equilibrium, heat losses have to balance heat production (Kothari, 2006; Bhatia and Malhotra, 2016). Heat transfer can take place by means of conduction (either through air or fibres), direct radiation, from fibre to fibre, and convection of the air (Ukponmwan, 1993; Bhatia and Malhotra, 2016).

Many studies, undertaken on textile fabrics, have demonstrated the close relationship between the thermal resistance of the fabric and its thickness (for example Whiteley *et al.*, 1980; Ukponmwan, 1993; Özdil *et al.*, 2007; Jun *et al.*, 2009; Wardiningsih, 2009; Ding *et al.*, 2011), mainly due to air entrapment within the fabric increasing with the thickness of a fabric, the thermal resistance of air being much higher than that of the fibre. Many studies have regarded thermal and moisture resistance as separate processes, in terms of comfort. Nevertheless, moisture vapour resistance and sorption of a fabric influence its thermal insulation, thus the two should be considered as a single process (Li, 2001).

Although there are various methods of assessing the comfort related properties of fabrics, the fact that these methods produce results on fabrics that are difficult to apply to clothing systems, has led to the development of alternative systems, such as thermal manikins, which can measure the thermal resistance of clothing under conditions which can imitate those encountered during wear (Fan and Chen, 2002). Various methods of testing comfort have been developed over the years, with the sleeping bag test being the original testing method (Fan, 2006), and thermal manikin testing being the modern testing method of choice (Celcar *et al.*, 2008).

The precise role of fibre type and properties in determining fabric thermal resistance, and also water vapour resistance, is still unclear, as evident from the often contradictory results obtained by different researchers in this respect. Furthermore, the effect of fibre type on thermal insulation and moisture vapour resistance of clothing ensembles has not been studied to the same extent as for fabrics. Certain studies have been conducted in an attempt to understand what determines and influences the comfort and comfort related properties of clothing (Dave *et al.*, 1987; Gericke and Van der Pol, 2010; Onal and Yildirim, 2012; Dominiak and Frydrych, 2013; Manshahia and Das, 2014a; etc.). Nevertheless, except for the very limited recent study, by Stoffberg *et al.*,2016, no study has specifically been undertaken to investigate the effect of fibre blend on the comfort of clothing ensembles. It was in the light of this, that the present study was undertaken.

FIGURE 1: FRONT VIEW OF WALTER™ (FAN, 2006B)

The main objective of the present research was to extend the preliminary study (Stoffberg *et al.*, 2016), and to determine the relative role and importance of commercial worsted suiting fabric fibre blend vis-à-vis fabric structural parameters, on the comfort related properties of clothing ensembles. Twelve wool and wool blend commercial suiting fabrics were sourced from South African clothing manufacturers and made up into identical men's suits. The comfort related properties, namely thermal and water vapour resistance and water vapour permeability, of 12 clothing ensembles, each containing a different man's suit, but the same wool/nylon underwear and cotton shirt, were measured on Walter™ (Figure 1), a thermal sweating manikin, by a team at Cornell University (USA), and the results so obtained subjected to multi-linear and multi-quadratic analyses, as dependent variables, with the various fabric parameters, namely weight, thickness, density, porosity, air permeability and % wool, as independent variables.

METHODOLOGY

Materials

Twelve commercial wool and wool/polyester fabrics, typical of locally produced high quality men's worsted suiting material used for suits produced in South Africa, were selected according to structure, weight and blend, and made up into 12 identical suits. The fabrics were selected so that the effect of suiting fabric fibre blend on the comfort related properties of clothing ensembles could be determined.

Fabric tests

The fabrics were tested (10 tests each), by the CSIR in Port Elizabeth, for weight (mass) (SANS

79:2004 (2010-01-15) or (SABS SM 79)), thickness (ASTM D1777-96) and air permeability, using standard test methods. Prior to testing, the fabrics were conditioned under standard atmospheric conditions for 24 hours at 20˚C ± 2˚C, and 65 % ± 2 % RH (SABS, 2015). Comfort related properties (Thermal Resistance (R_t) and Water Vapour Resistance (R_{et})) were tested by Cornell University (USA). The results obtained on the twelve clothing ensembles as well as on the suiting materials are shown in Table 1. Fabric Density (g/cm^3) of fabrics was calculated, by dividing the fabric mass per unit area (g/cm^2) by fabric thickness (cm). Fabric porosity was calculated as follows:

$$\text{Porosity} = 1 - \left(\frac{Fabric\ Density}{Fibre\ Density}\right) x100\%$$

Description of the thermal manikin (Walter™) and its function

The human body has approximately six million sweat glands, far more than any sweating manikin can imitate by using a system of tubes throughout the manikin (Fan, 2006). Walter™ is the first thermal manikin consisting of mainly water enclosed in a high strength breathable fabric skin (Fan, 2006). The 'skin' of the manikin (Figure 1) is made of a waterproof, but moisture permeable fabric, similar to the human skin, allowing moisture, but not liquid water, to pass through the fabric (Celcar *et al.*, 2008). Pumps, inside the manikin body, are regulated to keep the core temperature similar to that of a human being (37˚C), by controlled heating of the water inside the manikin (Fan and Qian, 2004). The heated core temperature supplies warm water to the extremities of the manikin, thus the temperature of the extremities depends on water flow. The 'skin' temperature can be changed, as required, or a 'skin', with different moisture permeability properties, can be used on the manikin to increase or decrease the rate of moisture vapour transmission (Fan, 2006).

Walter™ maintains its shape by being fully filled with water, even though water constantly evaporates from its 'skin' during testing, thereby simulating human perspiration. The water flow, within Walter™, can be adjusted by using five valves, situated at the head, legs and arms (which should be pre-adjusted) and four smaller valves at the ends of the arms and legs (adjusted during operation). The mean skin temperature of the manikin can be controlled by specialized software, which regulates the rate of the pumps (Fan and Qian, 2004; Fan, 2006b).

The total thermal resistance (R_t), including the insulation of the clothing and the layer of air on the surface, is calculated by using the following equation:

$$\boldsymbol{R_t} = \frac{A_S(T_S - T_a)}{H_S + H_P - H_e}$$

where A_s is the surface area of the manikin, T_S is the mean skin temperature, T_a is the temperature of the environment, H_s is the heat supplied to the manikin by external sources (such as heaters), H_p is the heat generated by the pump (assuming that all energy produced by the pump is converted into heat) and H_e is the evaporative heat loss (Fan and Chen, 2002).

To calculate the total moisture vapour resistance (R_{et}) of clothing, when using Walter™, the following formula is used:

$$\boldsymbol{R_{et}} = \frac{A_s(P_{ss} - P_{sa}H_a)}{H_e} - R_{es}$$

where A_s is the surface area of the manikin (Walter™), P_{ss} is the pressure of the saturated water vapour on the skin of the manikin, P_{sa} is the pressure of the saturated water vapour at ambient temperature, H_a is the relative humidity (RH %) at ambient temperature, H_e is the evaporative heat loss and R_{es} is the pre-calibrated moisture vapour resistance of the fabric skin (R_{es} = 8.36 m^{2}Pa/W) (Fan and Hunter, 2009).

The moisture permeability index I_m) can be calculated as follows (Özdil *et al.*, 2007; Mukhopadhyay and Midha, 2008; Fan and Hunter, 2009; Voelker *et al.*, 2009; Bedek *et al.*, 2011):

$$\boldsymbol{I_m} = \mathbf{60.6}\left(\frac{R_t}{R_{et}}\right)$$

TABLE 1: TEST RESULTS ON THE CLOTHING ENSEMBLES AND SUITING FABRIC

Fabric code	Fibre Content*	Fabric Weave*	Thermal Resistance (R_t)**	CV%	Moisture Vapour Resistance (R_{et})**	CV%	Moisture Permeability Index (I_m)**	Air Permeability (Pa)*	Calculated Porosity (%)*	Calculated Apparent Density (g/cm³)*	Thickness (cm)*	Weight (g/cm²)*
			(C.m²/W)		(Pa.m²/W)							
C14051/9	60% Wool/ 40% Polyester	Twill	0.238	2.0	43.0	1.7	0.336	7.15	57.1	0.58	0.030	0.017
C23021/9	100% Wool	Twill	0.238	1.6	43.0	0.9	0.335	7.62	63.3	0.48	0.031	0.015
C23171/19	100% Wool	Twill	0.242	3.9	41.8	2.6	0.349	9.47	59.4	0.54	0.034	0.018
C23261/19	100% Wool	Twill	0.238	1.3	42.1	1.4	.343	9.63	61.8	0.50	0.033	0.017
C12071/7	80% Polyester/ 20 % Wool	Twill	0.240	3.3	41.7	1.5	0.349	12.92	59.3	0.56	0.030	0.017
C22261/9	65% Polyester/ 35 % Wool	Twill	0.236	2.4	40.8	1.7	0.352	10.03	64.6	0.48	0.039	0.019
C21231/7	55% Polyester/ 45% Wool	Plain	0.229	2.3	39.0	2.3	0.356	116.22	67.3	0.44	0.027	0.012
C21241/9	100% Wool	Plain	0.242	2.3	40.1	1.8	0.365	50.3	66.7	0.44	0.036	0.016
C21251/19	100% Wool	Plain	0.240	2.7	41.9	2.2	0.348	16.58	61.0	0.52	0.027	0.014
C13211/25	70 % Wool/ 30% Polyester	Plain	0.230	3.6	39.5	2.1	0.353	29.65	58.6	0.55	0.026	0.014
C23191/26	100% Wool	Plain	0.236	2.6	43.4	1.8	0.329	14.77	60.9	0.52	0.038	0.020
C32221/28	50 % Wool/ 50% Polyester	Plain	0.237	1.4	41.6	1.6	0.346	12.72	59.5	0.55	0.029	0.016

* Suiting fabric
** Clothing ensemble

I_m ranges from 0 for completely impermeable fabric or clothing to 1 for completely permeable fabrics or clothing.

Clothing ensemble tests

The two main parameters, measured on the clothing ensembles, are Thermal Resistance (R_t) and Water Vapour Resistance (R_{et}), with Moisture Permeability Index (I_m), taken as an overall measure of comfort, being derived from R_t and R_{et}. Thermal Resistance (R_t) or insulation, as defined by Morris (1953), refers to how successfully fabric can maintain body temperature at normal levels under stable conditions. Thermal insulation, or resistance, can also be referred to as the warmth (heat) retaining property of a textile material, or clothing (Fan and Hunter, 2009). Water vapour resistance (R_{et}) can be taken as "the total resistance against the transport of water vapour through the textile fabric" (Gericke and Van der Pol, 2010), while the moisture permeability index (I_m), derived from R_{et} and R_t, has been defined by Hatch, 1993, as "the rate at which water vapour diffuses through a fabric" and is taken as an overall measure of comfort.

The 12 suits are shown mounted, always over the same wool/nylon underwear (vest and long pants) and cotton shirt, on Walter™, in Figure 2. The comfort related properties (especially thermal resistance, water vapour resistance and moisture permeability index) of the twelve clothing ensembles were measured on Walter™ at Cornell University (USA), under standard atmospheric conditions as follows, with 5 repeat tests per suit being carried out:

i) Water loss was calibrated and done while running the manikin at normal conditions (20^0C ± 1.5^0C and 65% ± 6% RH).
ii) While waiting for a stable state of the water loss and control temperature, the balance reading (R) was recorded and a small quantity W (the amount of sweat accumulated in 1 or 2 hours) of water was added in the water container, thus the balance reading increases.
iii) The initial time was recorded as t_1 (in hours). After the balance reading (R) dropped, the

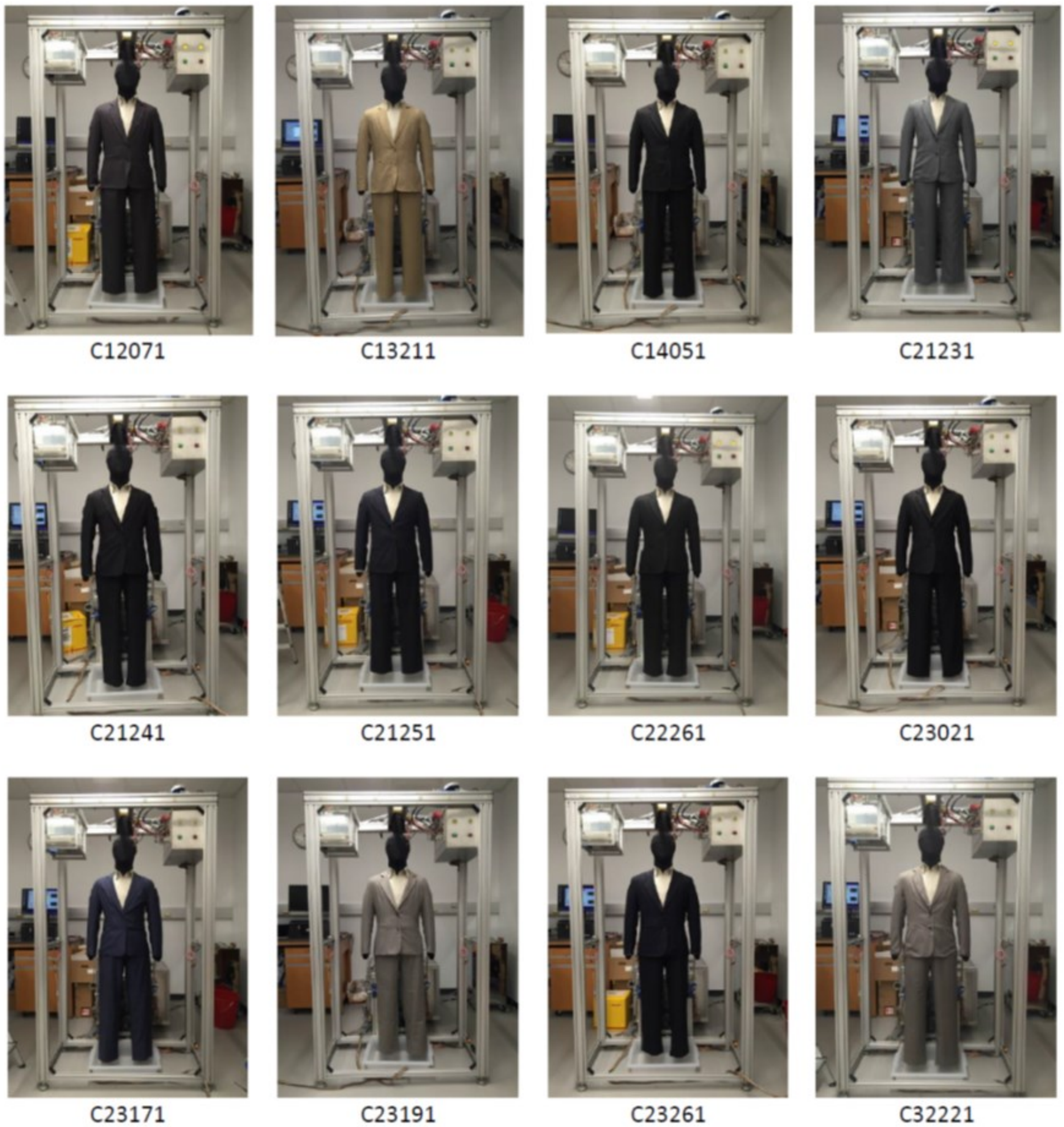


FIGURE 2: WALTER™, THE FABRIC SWEATING MANIKIN, DRESSED IN TWELVE DIFFERENT SUITS

time was recorded again, now as t_2.

iv) The next step required one to set K=1 (K=1.099 for the Gore-Tex 'skin') in the configure step.

v) Steps i-v were repeated three times, with Walter™ wearing each of the twelve suits (three times per suit), to establish a CV%.

Statistical analyses

Linear, multi-linear and multi-quadratic analyses were carried out on the results, but only those of the latter have been reported, since they best explained the variations in the comfort related properties of the clothing ensembles.

RESULTS AND DISCUSSION

From Table 1 it can be seen that although the suiting fabrics differed in structure, fibre blend

TABLE 2: PEARSON CORRELATION MATRIX

	Correlation (r)							
	Thickness (cm) *	Weight (g/cm^2) *	R_t (˚C.m²/W)**	R_{et} (Pa.m²/W)**	I_m **	Air Permeability (Pa) *	Apparent density (g/cm^3)*	Porosity (%)*
Thickness (cm)*	1.000							
Weight (g/cm^2)*	0.814	1.000						
R_t (˚C.m²/W)**	0.412	0.464	1.000					
R_{et} (Pa.m²/W)**	0.294	0.575	0.518	1.000				
I_m **	-0.110	-0.414	-0.041	-0.874	1.000			
Air permeability (Pa)*	-0.301	-0.664	-0.565	-0.739	0.536	1.000		
Apparent density (g/cm^3)*	-0.301	0.305	0.107	0.429	-0.445	-0.623	1.000	
% Porosity *	0.268	-0.331	-0.161	-0.492	0.493	0.665	-0.988	1.000

* Suiting fabric
** Clothing ensemble

(cyan) r > 0.426 for significance at 99.9% confidence level
(yellow-green) r > 0.340 for significance at 99% confidence level
(pink) r > 0.261 for significance at 95% confidence level

and certain structural parameters, the comfort related properties of the clothing ensembles, as measured on the thermal manikin, were very similar, indicating the moderating effect of the air entrapped between the layers of clothing, as well as underwear on the measured comfort properties.

Pearson correlation matrix

The Pearson correlation matrix (Table 2) illustrates the interrelationships between the various dependent and independent variables, thermal resistance (R_t), moisture vapour resistance (R_{et}) and moisture permeability index (I_m) being the dependent variables, with suiting fabric thickness, weight, air permeability (AP), apparent density (derived) and porosity (derived) the independent variables. Air permeability and porosity are both functions of fabric thickness and weight, and strictly speaking can therefore not be regarded as true independent variables. Nevertheless, for the purpose of the regression analyses, they have been included as independent variables.

Table 2 shows that the clothing ensemble moisture vapour resistance (R_{et}) was best correlated (r = - 0.739) with suiting fabric air permeability and weight (r = 0.575), and R_t and I_m with fabric air permeability, r = - 0.565 and r = 0.536, respectively. It is clear, therefore, that taken singly, and ignoring fabric weave and fabric blend, the three clothing ensemble dependent variables (R_t, R_{et} and I_m) were most closely related with the air permeability of the suiting fabric. This will be further investigated in the next section.

Multi-quadratic regression analysis

By using multi-quadratic regression analysis, allowance is made for non-linear relationships and in this particular case, also for interactions. All the independent variables, namely suiting fabric thickness (cm), weight (g/cm^2), density (g/cm^3), porosity (%) air permeability (Pa), and % wool, were used in the multi-quadratic regression analysis. The following model was used:

$$y = b_0 + b_1{*}X_1 + b_2{*}X_1^2 + b_3{*}X_1{*}X_2 + b_4{*}X_2 + b_5{*}X_2^2 + b_6{*}X_2{*}X_3 + b_n{*}X_n + b_{n+1}{*}X_n^2 + b_{n+2}{*}X_n{*}X_{n+1} + \quad (1)$$

y = Dependent variable

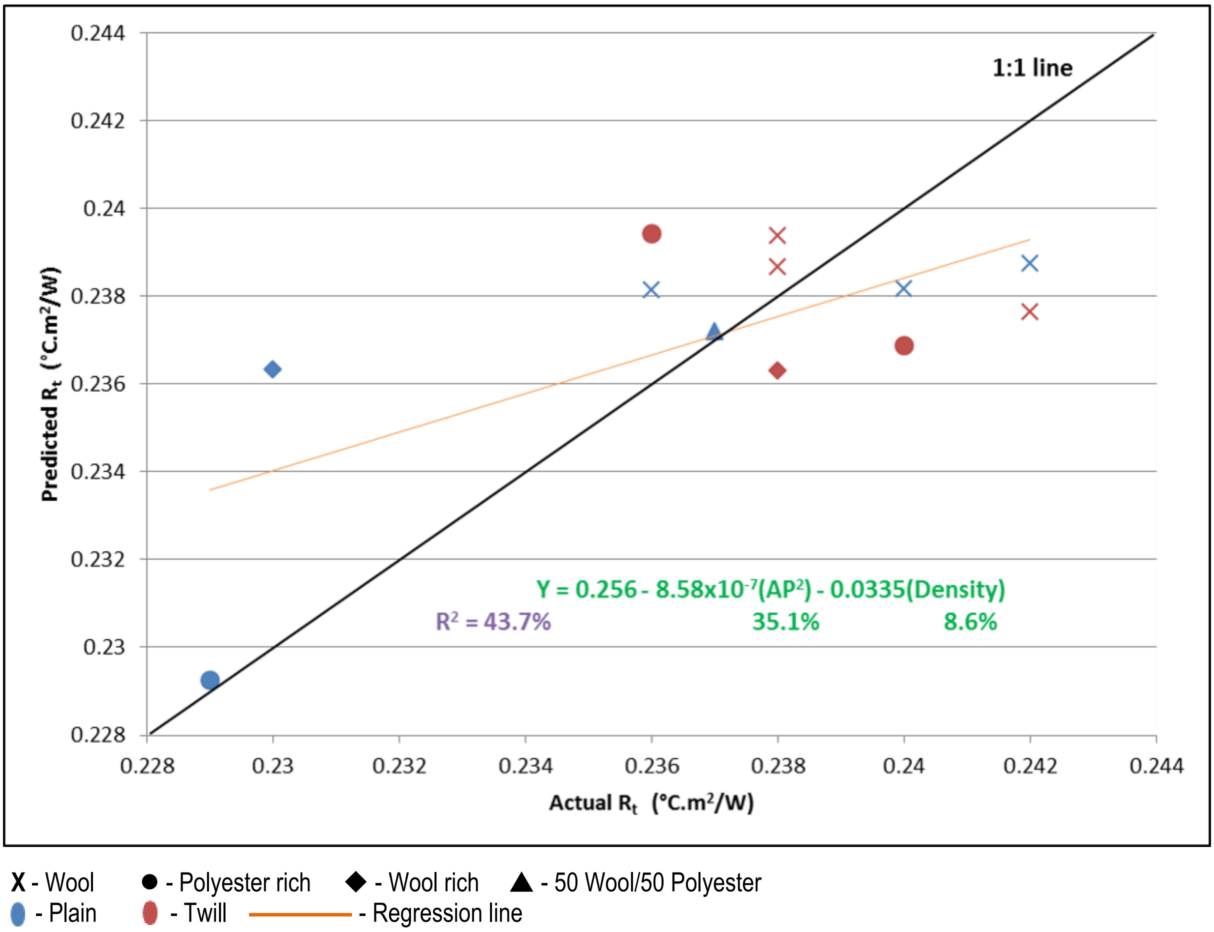


FIGURE 3: PREDICTED VS. ACTUAL CLOTHING ENSEMBLE R_t

b_0 = Intercept
b_n = Coefficients/regression gradient
x_n = Independent variable value

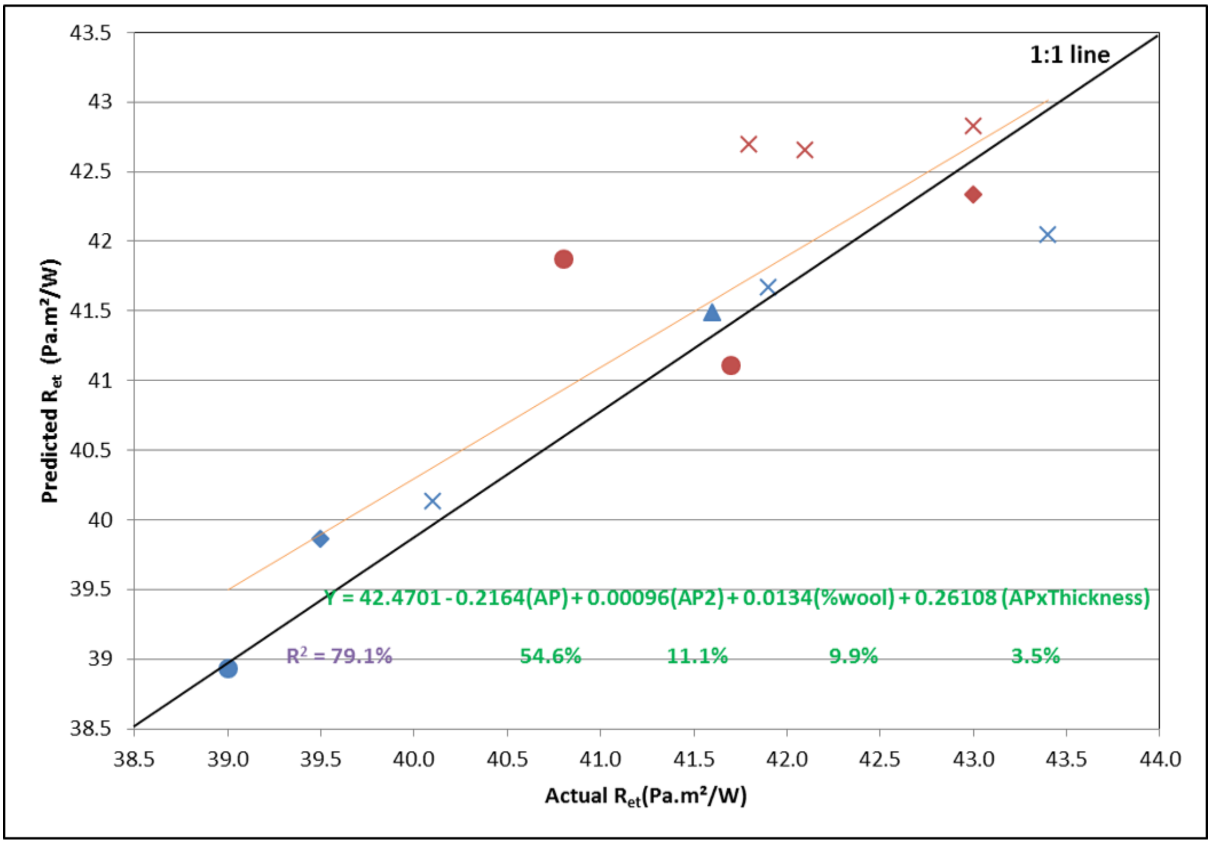
The multi-quadratic regression equations analyses yielded correlations, or percentage fit (R^2 x 100%) ranging from 43.7% to 79.1%, the magnitude of which reflects the accuracy with which the corresponding dependent variable can be predicted from the independent variables appearing in the regression equation. Although more terms, statistically significant (at the 5% probability level), could have increased the correlation coefficient and percentage fit, this would have made it difficult to interpret and understand the results. Thus, it was decided to disregard those independent parameters which contributed less than 1%, to the total fit, as well as porosity, due to the latter being a function of fabric density.

Thermal resistance (R_t)

The multi-quadratic regression analyses, involving R_t, yielded the following significant regression equation:

R_t (℃.m^2/W) = 0.256 - 8.58x10^{-7}(AP)^2 - 0.0335 (density) (2)
Contribution to R^2 x 100 = 35.1% + 8.6% = 43.7%

Equation (2) indicates that only the suiting fabric air permeability (AP) and density were statistically significant, contributing 35.1% and 8.6%, respectively, to the overall percentage fit of 43.7%, with R_t a quadratic function of air permeability. The thermal resistance (R_t) decreased with an increase in suiting fabric air permeability and density, most probably due to their effect on air entrapment within the suiting fabric. Nevertheless, the two variables combined only accounted for some 44% of the variation in the clothing ensemble R_t, the remaining 56%



X - Wool ● - Polyester rich ◆ - Wool rich ▲ - 50 Wool/50 Polyester
● - Plain ● - Twill ——— - Regression line

FIGURE 4: PREDICTED VS. ACTUAL CLOTHING ENSEMBLE R_{et}

being unexplained. From Figure 3 it is apparent that the various points, representing the different blends and weave structures, lie more or less randomly around the regression line. This suggests that, once allowance is made for possible associated differences in fabric air-permeability, neither wool content nor fabric weave had a statistically significant or consistent effect on the thermal resistance of the clothing ensembles.

Although the data points lie fairly scattered, it should be noted that the two suit ensembles, with the highest actual thermal resistance were made from 100% wool fabric, but this appears to be due to the fact that the air permeability and density of these two suiting fabrics were lower than those of the other fabrics.

Water vapour resistance (R_{et})

The multi-quadratic regression analysis on R_{et}, yielded the following best fit regression equation:

R_{et} *(Pa.m²/W) = 42.5 - 0.216(AP) + 0.00096(AP)* ^{2} *+ 0.013(%wool) + 0.261 (AP x Thick)* (3)
Contribution to R^2 x 100 *= 54.6% + 11.1% + 9.9% + 3.5% = 79.1%*

Equation (3) shows that the suiting fabric air permeability had by far the most significant effect on the clothing ensemble R_{et} (on its own contributing some 66% to the overall percentage fit of 79.1%), with the %wool and fabric thickness also playing some role, the regression equation explaining almost 80% of the variation in R_{et}. The regression equation also shows that the relationship between R_{et} and air permeability is quadratic, not linear, with R_{et} generally decreasing as the suiting fabric air-permeability increases.

In Figure 4, the predicted R_{et} has been plotted against the actual, from which it can be seen that the various points, representing the different

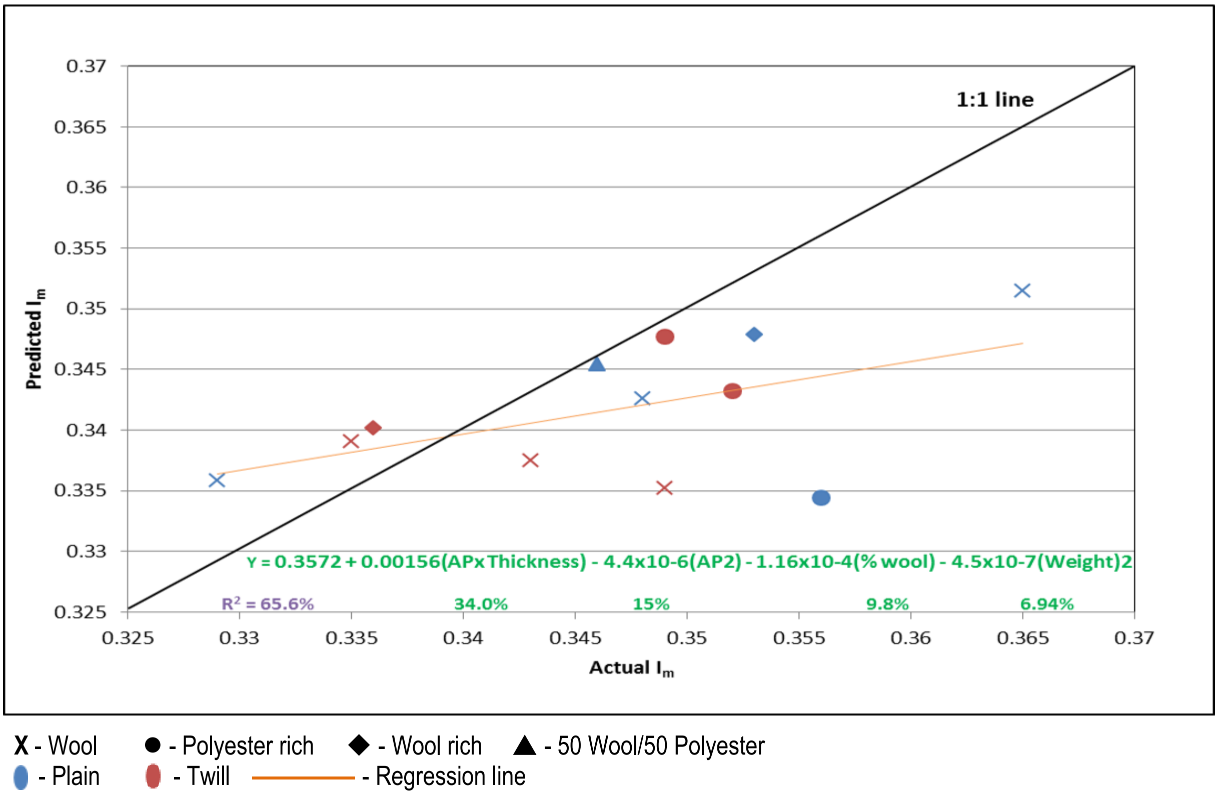


FIGURE 5: PREDICTED VS. ACTUAL CLOTHING ENSEMBLE I_m

weaves and blends tend to, lie randomly scattered around the regression line, indicating that weave does not affect R_{et}, except in so far as it affects either fabric air permeability or thickness, or both. According to regression equation (3), variation in the percentage wool explains about 10% of the variation in R_{et}, the water vapour resistance of the clothing ensemble tending to increase as the percentage wool in the suiting fabric increases, which is a little surprising, wool being a hygroscopic fibre.

Water vapour permeability index (Im)

Water vapour permeability index (I_m), derived from R_t and R_{et}, is often taken as an overall measure of the comfort of a garment.

The multi-quadratic analyses carried out on the clothing ensemble water vapour permeability index (I_m) results, yielded the following significant regression equation, the predicted *vs.* actual results being plotted in Figure 5.

$I_m = 0.357 + 0.00156(AP \times thickness) - 4.4\times10^{-6}(AP)^2 - 1.16\times10^{-4}(\%wool) - 4.5\times10^{-7}(weight)^2$ (4)

Contribution to R^2 x 100 *= 34% + 15% + 9.8% + 6.9% = 65.6%*

According to regression equation (4), suiting fabric air permeability(AP), on its own, together with its interactive term with the suiting fabric thickness, contributed most (49%) to the overall percentage fit of 65.6%, with suiting fabric wool content and weight, also having statistically significant, though lesser important, effects. Equation (4) explains some 66% of the variation in I_m. The water vapour permeability index (I_m) of the clothing ensemble decreased as the percentage wool in the suiting fabric increased once again, an unexpected result which requires further investigation.

Figure 5 shows that the points generally lie fairly randomly scattered around the regression line, with weave structure not appearing to have a consistent effect, except in so far as it may have had an effect on fabric air permeability and thickness.

A larger I_m is generally regarded as desirable from a clothing comfort point of view, the results obtained here indicating this can be achieved by changing the fabric air permeability and thickness, rather than by changing the wool content of the fabric. A relatively thin, light-weight fabric, with a relatively low entrapped air will however nearly always have a relatively low thermal resistance or heat insulator.

From the above it is apparent that the air permeability of the suiting fabric generally had the main effect on the comfort related properties of the clothing ensembles, as measured on the sweating manikin.

SUMMARY AND CONCLUSIONS

Twelve commercial worsted suiting fabrics, differing basically in weave (plain and twill weave), weight and percentage wool, were used to make twelve identical suits. The effect of suiting fabric properties, notably weave, thickness, air permeability, weight and % wool, on the comfort related properties, namely thermal resistance (R_t), water vapour resistance (R_{et}) and water vapour permeability index (I_m), of a clothing ensemble, comprising a suit over a wool/nylon underwear and cotton shirt, as measured by means of a thermal sweating manikin Walter^{TM}, was investigated and analysed, using linear, multi-linear and multi-quadratic regression analyses. Only the results of the multi quadratic analyses have been reported and discussed, since they gave the highest correlation and fit to the data.

The water vapour permeability index (I_m) of the clothing ensemble, considered to be an overall measure of comfort, was derived from the thermal (R_t) and water vapour (R_{et}) resistance of the clothing ensembles.

In general, it was found that variations in the suiting fabric air permeability explained more of the variations in the clothing ensemble thermal and water vapour resistance, than did the other suiting fabric parameters, such as fabric blend (% wool), weight and thickness. This indicated that the fabric parameters play a different role in the comfort related properties, when measured on a clothing ensemble, or suit, than in the comfort related properties when measured on the fabric as such. This certainly warrants a more in depth study.

An increase in suiting fabric air permeability was generally associated with a decrease in both the thermal (R_t) and water vapour (R_{et}) resistances of the clothing ensemble, and with an increase in the water vapour permeability index (I_m) of the clothing ensemble.

The percentage wool in the suiting fabric had a statistically significant, though small, effect on the water vapour resistance (R_{et}) and water vapour permeability index (I_m) of the clothing ensemble, the former increasing and the latter decreasing as the percentage wool increased, which is somewhat surprising, since wool is a hygroscopic fibre and one would have expected the opposite effect. Nevertheless, the contribution of wool content, to the overall statistically derived percentage fit, was small, being approximately only 10% absolute, compared to that of air-permeability, which was of the order of 50%, when its interactions with other fabric parameters, such as thickness, were also included.

This study indicated that there was not such a good or direct relationship between suiting fabric properties and the clothing ensemble comfort related properties, as previously found between the corresponding fabric properties and fabric comfort related properties. This is not entirely unexpected since, for example, in the clothing ensemble, the air layers, entrapped between the manikin, underwear, shirt and suit, can be expected to have a relatively large influence on the comfort related properties of the ensemble, thereby possibly overshadowing the effect of changes in suiting fabric properties as such. In a follow-up study, the comfort related properties of the 12 suiting fabrics will be measured and related to those of the clothing ensembles, as measured on Walter^{TM} here, and this will form the subject of a second paper

Future Research

The results of this study cannot be regarded as conclusive, and further work is necessary. Such further work should follow a similar approach to that used here, but covering an even larger number, say 36, of and far more diverse commercially available worsted type suiting fabrics, in wool and wool blends. Furthermore, the comfort related properties should again be measured on a sweating manikin, such as Walter™, under dynamic conditions of changing relative humidity and temperature, in order to assess the effect of the heat of sorption properties of wool on the comfort related properties of the clothing ensemble. The thermal related properties of the suiting fabrics should also be measured on, for example, a Permetest, and the results so obtained related to those obtained on the clothing ensembles.

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