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Impact of varying lactate concentration in sweat on liquid moisture transmission behaviour of layered ensembles

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The present study is focussed on the impact of change in the lactate concentration (43 mM and 22 mM) in sweat solution on liquid moisture transmission behaviour through the clothing. The sweat solution with higher concentration of lactate (43 mM) shows delayed wetting at the top surface both in case of individual layer and multi-layer fabric ensembles, i.e. it takes longer time to wet the top surface in spite of the lower contact angle made by it. Significant difference is observed in in-plane transmission behaviour of both the sweat solutions in the case of multi-layered ensembles. In case of multi-layered ensembles, wetting time reduces drastically, even though both the ensembles consist of polyester knit as the inner surface possessing wetting time is 50 s approximately. Sweat solution with higher lactate concentration also shows higher cross-planar transmission rate as compared to in-plane transmission. Uni-directional seamed multi-layered spacer fabric exhibits better overall moisture management coefficient as compared to bi-directional seamed spacer ensembles with sweat solution containing higher lactate concentration. Middle layer also plays a vital role in altering the overall liquid moisture transmission behaviour.

Keywords: Lactate, Moisture transmission behaviour, Nylon, Polyester, Polyurethane, Spacer fabric, Sweat, Surface tension

1 Introduction

Liquid moisture transport is one of the important aspects for comfort of functional garments. Moisture is produced in the body as a result of metabolic heat which is readily dissipated through the clothing as sweat [1-3]. The amount of moisture generated may vary depending upon the nature of activity, gender and maturity rate. At rest, nearly 60mL/h of water vapour is released from human body under ambient conditions. Moderate exertion (walking) increases that amount to about 450mL/h. During sports activity, e.g. tennis or cycling, the metabolic heat increases to about six times and perspiration nearly 14 times (840mL/h.). If the moisture remains inside the fabric ensembles, this may lead to heat debt inside the body[4]. Fabric worn next to skin should exhibit lower in-plane transmission and higher cross-plane transmission in order to keep skin dry. The liquid moisture transport occurs through two mechanisms, viz wetting and wicking[5]. This is mainly determined by the surface tension (wetting), effective capillary pore distribution and pathways (wicking). Transport of water in fabric can take place in two different ways, viz (i) along the plane of the fabric and (ii) perpendicular to the plane of fabric governed by longitudinal and transverse wicking respectively [6].

The liquid moisture transmission is affected by various factors viz the layering of ensembles, composition of layers, sweating rate and solutes present in the sweat. It has been reported that when a person performs the prolonged exercises, two major solutes lactate (LAC^-) and ammonia (NH_3) are excreted in sweat[7]. The lactate in sweat is derived mainly from anaerobic glycolysis within the sweat glands. The concentration of lactate and ammonia vary from person to person. The cause of variability in sweat lactate and NH_3 may be accounted to their dependence on factors, such as sweating rate (SR), sweat acidity, and the transport of other ions in the duct of the sweat gland. Derbyshire *et al*[8]. observed that the sweating rate is inversely proportional to the generation of sweat lactate. In females, as the sweating rate is less, the generation of sweat lactate is higher (43-100 mM), whereas in male lactate concentration is lower (10-22 mM). The increase in lactate generation in sweat may alter the transmission rate of liquid moisture through the clothing. This, in turn, not only alter heat transmission properties but also thermo-physiological comfort of wearer.

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The accumulation of liquid moisture inside the clothing layers is issue of great concern when a person sweats profusely. This becomes more critical when the solutes of sweat vary in concentration and they may condense inside the structure, thereby closing the pores of the clothing[9]. This variation in solutes of sweat depends on differences in gender, their age, maturity level and activity level. This, in turn, gives rise to different microclimatic issues, which need to be managed to sustain life in extreme climatic conditions[10].

Till date, extensive study has not been carried out using variaties of sweat and their effect on thermo-physiological comfort of wearer. In an earlier study[11], the influence of sweat on liquid moisture transmission of individual fabric and layered ensemble is investigated. However, the effect of change in lactate concentration in sweat on liquid moisture transmission behaviour of multilayer ensembles has not been investigated so far. Thus, present study is the extension of the above study, wherein the effect of change in lactate concentration in sweat has been studied. This will certainly help in developing suitable garment for varying strenuous activity, genders and maturity level.

Therefore, by considering the above-mentioned aspect, two different sweat solutions representing female and male sweat were selected for the present study. The present selection was made depending on differences in sweating rates of male and female. Further, it has been reported in earlier studies[12] that the skin surface has an acidic *p*H, called the ‘acid mantle”. This acidic surface *p*H as well as its concomitant *p*H gradient over the stratum corneum (SC) are important for a good skin condition, controlling the presence of resident skin microflora as well as supporting important physiological processes like the formation of an optimal structure of the lipid barrier and SC homeostasis. Skin with *p*H < 5.0 is in better condition than skin with *p*H > 5.0. Growth of *S. epidermidis*, under *in-vitro* acidic *p*H conditions (*p*H 4.7) and in the presence of lactate, is enhanced when compared with neutral *p*H, whereas growth of *S. aureus* is strongly inhibited under these acidic conditions. An acid *p*H seems to preserve the resident bacterial flora, whereas an alkaline *p*H causes dispersal from the skin. Hence, the concentration of lactate was varied such that *p*H of the sweat solution variants was reported to be acidic.

The findings of this study are expected to be realistic and important in designing and development of cold weather garment ensemble for different gender type depending on their activity level especially in case of military personnel and those performing combat activities.

2 Materials and Methods

2.1 Materials

Multi-layered ensemble is made using three different fabrics, viz polyester knitted (inner layer), polyester spacer/ polyester fleece (middle layer) and polyurethane coated nylon (outer layer). The details of specifications of constituent layers are given in Table 1.

The multi-layered ensemble was then stitched using lockstitch machine (JUKI ddl-8100). Two-ply spun polyester of linear density 28 tex, twist direction Z/S (ply/single) with overall tpm of 578 was used for stitching. Stitch density was kept constant at 3 stitches/ inch. Stitching machine speed is set at 3000 rpm. Directions and pattern of stitching as unidirectional and bi-directional are shown in Fig. 1. The distance between adjacent seams is set as 2 cm wide.

Thickness of the seamed (unidirectional and bidirectional) and unseamed multi-layered ensembles was also measured using thickness measurement tester ASTM D 16777 (Table 2).

Before conducting the test, all the fabric samples were first conditioned at tropical atmosphere of 27 °C ± 2 °C and 65% ± 2% R.H. For each test, 15 samples were tested to minimise the error below 2%.

2.2 Preparation of Sweat Solution Variants

Standard sweat solution was prepared using ISO 3160/2, as it comprises 20 g/L NaCl, 17.5 g/L NH4Cl, 5 g/L acetic acid and 15 g/L d,l lactic acid with the *p*H adjusted at 4.7 by NaOH pellets. Concentration of lactic acid was varied for preparing

Table 1 — Specifications of fabrics used

Fabric	Construction	Filament/spun type	Porosity %
Polyester knit	Knitted (double jersey/interlock)	Multifilament (150D/144F)	79.4
Polyester fleece	Knitted with fleece on one side (fibres raised on the inner side)	Spun polyester	74
Polyester spacer	Knitted 3D structure (single jersey on both sides with spacer yarn in between)	Multifilament (outer), Monofilament (inner)	82.5
PU Coated nylon	Woven fabric (nylon filament with PU coating)	Multifilament (70D/24 F)	45.6

variants of sweat solution used for present study. Further, to prepare variants of sweat solutions, two beakers containing 100 mL of distilled water were taken. Then 2g of NaCl and 1.75 g of NH_4Cl were added separately in both the beakers and mixtures were stirred properly. After that, 0.467 mL of acetic acid was added in the solutions. Further, for making the variants of sweat solution, different quantity of lactic acid, whose concentration was fixed at 43 mM and 22 mM, was added to the respective beakers. The samples were homogenized by vortex mixing. Before any rheological measurements, all the samples were conditioned to equilibrate. The *p*H values of both the sweat solutions were noted as 3.7 and 5.8 respectively. The sweat solution was used for the testing of moisture management properties.

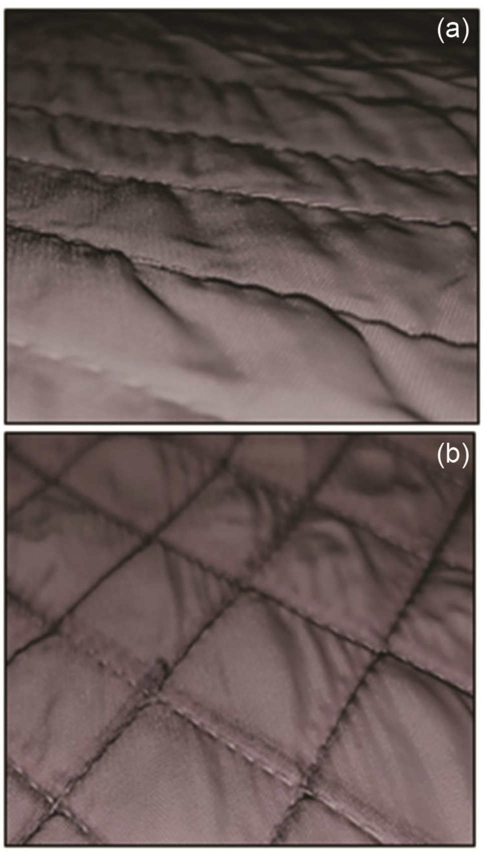

Fig. 1 — Seam pattern used in multi-layered ensembles (a) unidirectional and (b) bidirectional

2.3 Testing Procedure

For the assessment of liquid moisture transmission behaviour, moisture management tester was used[12]. Results in terms of top and bottom wetting time (measured by plotting the time versus moisture content and finding the time by which slope of such plot reaches tan 15°), spreading speed, absorption % and one-way transport capacity (OWTC) were obtained at the end of the test. Through these results, overall moisture management coefficient is then calculated for all the samples. ANOVA analysis was done; the % contribution of the different factors is evaluated based on the following expression:

$$\% \text{ Contribution} = \frac{(SS_f - df_f . Ve)}{SS_T} \times 100$$

where SS_f is the sum of square of the factor; df_f , the degree of freedom of the factor; Ve, the mean square of pooled error; and SS_T, the total sum of squares.

3 Results and Discussion

Liquid transmission behaviour of both the sweat solutions has been analysed in terms of their in-plane transmission behaviour (wetting time), cross-plane transmission behaviour (one way transport capacity), and overall moisture management capacity. It is observed that liquid transmission behaviour differs significantly when tested with different sweat solution (Table 3).

3.1 Wetting Time

For analysing the liquid moisture transmission behaviour of different sweat solutions, the contact angles made by both of the sweat solutions on different fabric ensembles are measured using sessile drop method respectively[13] (Table 4). It is observed that as the acidity of the sweat solution increases, the interfacial tension between surfaces decreases, resulting in the formation of lower contact angles by sweat solution containing higher lactate concentration.

Table 4 also shows that the in case of individual layers, the contact angle made by sweat solutions is different on different fabric. On the other hand, in the case of the all-multilayer ensembles, even though the top surface is common (polyester knit), the contact angle made by the sweat solution is different on both

Table 2 — Thickness, of multi-layered ensemble

Fabric type	Thickness, mm				
	Unseamed	Unidirectional		Bidirectional	
		At stitch junction	In between junction points	At stitch junction	In between junction points
Multi-layered spacer	2.91	2.50	3.10	2.24	3.50
Multi-layered fleece	2.25	2.15	2.89	2.08	4.02

Table 3 — ANOVA results of individual layer and multi-layered ensembles

Parameters	Wetting time		One way transport capacity		Overall moisture management capacity	
	$F_{Calculated}$	% Contribution	$F_{Calculated}$	% Contribution	$F_{Calculated}$	% Contribution
			Individual layer			
Fabric	35301.3	98	3447.4	95	244.47	93
Solution type	378.3	0.3	406.76	3.7	399.74	5.1
Fabric × solution type	200.10	0.2	38.23	1.04	41.53	1.5
			Multi-layered ensembles			
Layers	417.39	11	300.43	22.5	399.89	22
Seams	1220.05	61.3	419.10	63	571.45	63
Solution type	591.95	18	137.90	10.3	200.74	11.06
Layers × seam type	45.01	3	13.78	2	18.22	1.9
Layers × solution type	-	-	-	-	-	-
Seam type × solution type	33.65	2.4	52.05	0.6	4.56	0.4

F_{Table} values for $d_f(1,14)$= 4.60 and $d_f(2,14)$=3.64.

Table 4 — Contact angle made by different sweat solution

Fabric	Contact angle, deg	
	Sweat solution (22 mM)	Sweat solution (43 mM)
Polyester knit	130.1	111.9
Polyester spacer	133.6	113.6
Polyester fleece	150.7	120.7
PU coated nylon	91.8	77.1
Multi-layered spacer un-seamed	101.8	100.99
Multi-layered spacer uni-directional seam	149.5	132.4
Multi-layered spacer bi-directional seam	67.77	43.8
Multi-layered fleece un-seamed	140.1	129.1
Multi-layered fleece ni-directional seam	166.4	145.01
Multi-layered fleece bi-directional seam	90.67	72.8

seamed and unseamed multi-layered spacer and fleece ensembles. Further, it is seen that there is little difference in contact angle made by the both sweat solution in case of unseamed ensembles (multi-layer spacer and multi-layer fleece) but is found to change significantly with the insertion of seams. This is attributed to the impact of several parameters, viz the effect of subsequent layers, formation of the stitch holes and the resultant pathways, layer to layer contact and bulging of the fabric between the seam junctions.

Generally, research studies indicate [14] that at lower contact angle, wetting time will be less, but in contrast to that it is seen that there is no positive correlation (r^2 values 0.053 and 0.029 respectively) between contact angle and the wetting time of both the multi-layered fabric ensembles (Fig. 2).

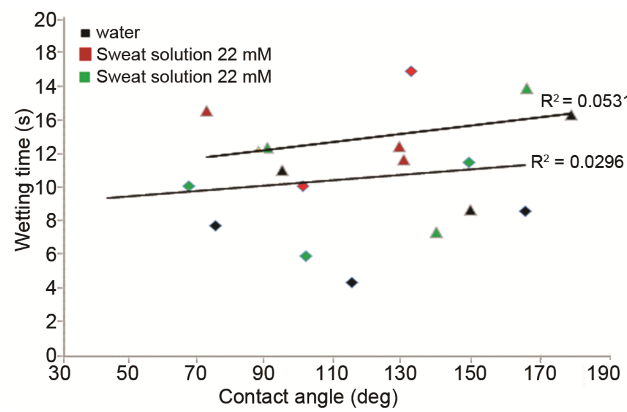

Fig. 2 — Correlation curves between contact angle and wetting time (using pure water and two levels of sweat solution in the case of both multi-layered spacer and fleece ensembles)

It is observed that the sweat solution with higher concentration of lactate (43 mM) (more acidic in nature) shows delayed wetting at the top surface, i.e. it took longer time to wet the top surface, in spite of lower contact angle made by it (Table 4). It also exhibits lower spreading speed in the plane of fabric. This is attributed to predominance of density of sweat solution containing higher concentration of lactate. The higher lactate concentration and, in turn, the presence of greater molecules of glucose, increases the net density of the solution [15]. This increased density of sweat solution assists in easy downward movement of sweat solution with higher concentration under the impact of gravitational force, thus leading to the better cross- plane transmittance of sweat solution through the fabric ensembles.

In the case of individual fabric layers, sweat solution with lower lactate concentration exhibits lower wetting time on the inner surface due to its better in-plane transmittance behaviour. Further, it may be added, that the difference in wetting time of sweat solution differing in the lactate concentration is significantly higher in case of polyester knit fabric [Fig. 3(a)]. This is due to the higher porosity values (Table 1), which, in turn, assists the sweat solution with lower lactate concentration to wet the top surface earlier i.e. in lesser time. On the other hand, polyester knit fabric also possesses lower thickness (Table 1), due to which sweat solution with higher lactate concentration, easily sweeps through the layer under the impact of gravitational force, resulting in higher difference in wetting time of both sweat solutions at the top surface. Both the sweat solutions show nearly same wetting time (180 s) at the top surface of polyester fleece fabric. This is due to raised fibrous structure which restricts the flow of sweat solution along the plane of fabric.

It is observed that both the sweat solutions show lower wetting time at the top surface of the multi-layered ensembles in comparison to that of the individual fabric layers. It is found that the wetting time of solutions in the multi-layered ensemble decreases drastically, even though all the multi-layer ensemble consists of polyester knit fabric, at the top surface; wetting time of polyester knit as individual layer is reported as 50-70 s. This is due to prominent role of the backing layer which assists in better spreading of liquid on the top surface at a lower time interval [Fig. 3(b)]. Further, it is noted that the sweat solution with higher lactate concentration shows higher wetting time in comparison to the sweat solution with lower lactate concentration at the top surface of the multi-layered ensembles. This is also attributed to predominance of density of sweat solution which enables the sweat solution with higher concentration of lactate to easily percolate downward under the impact of gravity, thus showing higher wetting time at top.

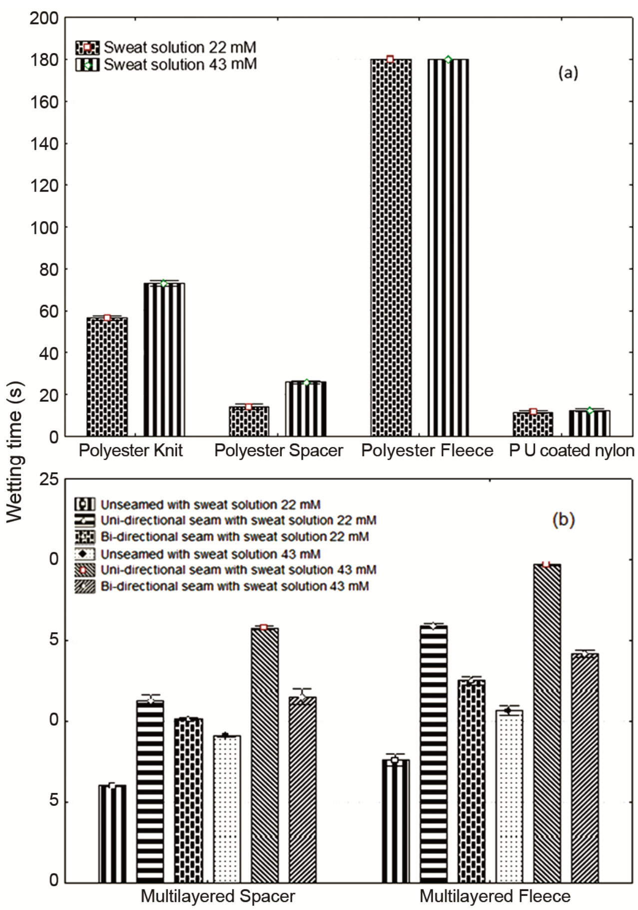

Fig. 3 — Wetting time shown by different sweat solution at top surface of (a) single layer and (b) multi-layered systems.

It is also revealed that in comparison to the unseamed and the bidirectional seamed structures, maximum difference in the wetting time of the sweat solutions is in the case of the uni-directional seamed multi-layer ensembles. It is attributed to the fact that the denser sweat solution may have easily swept downward through the stitch holes formed while seam insertion. Further, lower bulging between the layers and higher contact points may also have assisted in quick movement of sweat solution across the plane of fabric [Fig. 3(b)]. Minimum difference in wetting behaviour of both sweat solution is observed in the case of bi-directional seams as compared to the uni-directional and unseamed multi-layer ensembles. This is attributed to the greater bulging between the seam junctions, which retards the downward flow of the sweat solution and hence results in lower difference in the wetting time of the sweat solutions. Additionally, higher bulging creates greater surface area at the top which leads to better in-plane transmission of both the sweat solutions, leading to lesser difference in their wetting time. Marginal difference (difference being significant as per t-test) is observed in the case of the bi-directional seamed multi-layer spacer ensembles.

Further, from the ANOVA results, it is revealed that the impact of layers is most significant (nearly 98%) and role of solution type is only marginal in the case of individual layers (Table 3). On contrary, it is seen that in the case of the multi-layer ensembles, the impact of types of the layers is least (11%). Influence of seam type is found most significant (contributing nearly 61%), followed by solution type which accounts for 18% of total contribution (Table 3). It is assumed that on the insertion of seams, stitch holes are created and layer to layer gap is altered which further influence the wicking and spreading behaviour of liquid moisture.

3.2 Cross-plane Transmittance

In the present study, one-way transport index is an indicator of the cross-plane transmission rate of the sweat solutions across the fabrics. It is observed from Fig. 4(a) that the sweat solutions show different behaviour in terms of their one-way transport capacity, in the case of the both the individual and the multi-layered ensembles. One-way transport capacity of the sweat solution with higher lactate concentration is found higher as compared to the sweat solution containing lower lactate concentration in case of both individual layer fabric and the multi-layer ensembles [Figs 4 (a) & (b)]

In the case of individual fabrics [Fig. 4 (a)], the significant difference in cross plane transmission rate

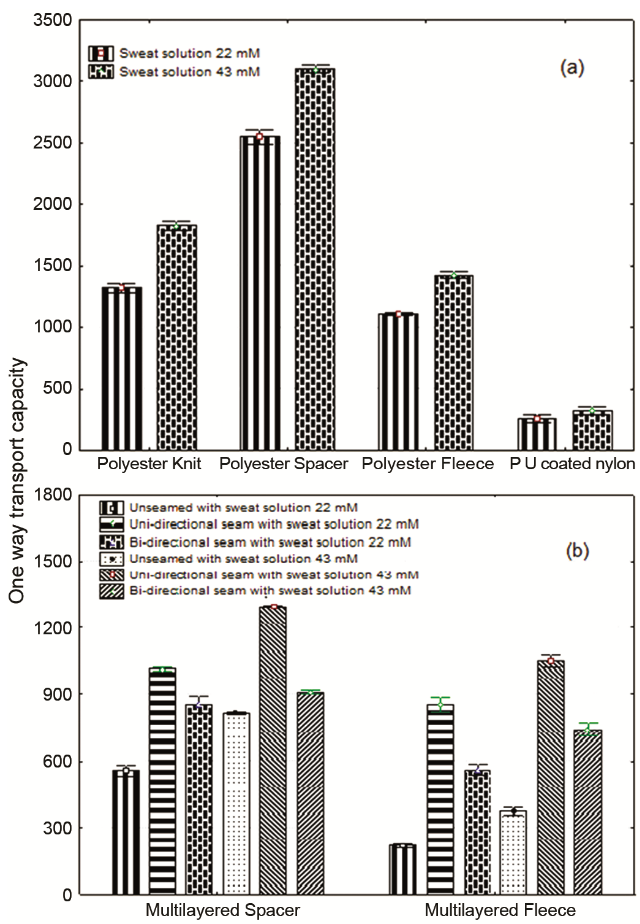

Fig. 4 — OWTC of water and sweat for different fabrics using sweat and water (a) single layer and (b) multi-layered systems

of both the sweat solutions is observed in the case of polyester spacer fabric in comparison to other individual fabrics. In the case of the multi-layered ensembles with spacer as middle layer [Fig. 4(b)], the sweat solution with higher lactate concentration exhibits higher cross plane transmittance. This is primarily because of the two factors, first one is characteristic of middle layer (porosity of spacer) and other is the impact of density of sweat solution as explained earlier[9].

It is also observed that the difference in one-way transport capacity of both the sweat solutions (with higher lactate concentration and lower lactate concentrations) is found significantly higher, especially in the case of uni-directional stitched fabric ensembles as compared to the un-seamed and bi-directional stitched structure. It is due to the formation of stitch hole at the junction points and lower bulging between the layers which results in better cross-planar transmission of sweat solution containing higher lactate as compared to latter. It is also important to mention here, that the marginal difference in cross-planar transmission of the sweat solutions is observed in the case of bi-directional seamed multi-layer spacer ensembles. This is due to predominance of surface area over density, as it is assumed that with the increase in surface area, the liquid easily spreads, resulting in better in-plane transmission as compared to the cross-plane transmission for both the sweat solutions. Secondly, the spacer fabric being porous further assists the process.

In addition to that, it is clear from Fig. 4 (b) that as the lactate concentration increases in sweat, the cross-planar transmission rate also increases in all the case of multi-layered ensembles. From ANOVA results (Table 3), it is revealed that in the case of individual layer fabrics, impact of the fabric type on cross-plane transmission of the liquid moisture is most significant (nearly 95%) followed by the contribution of solution type (3.7%). This can be explained on the basis of difference in structural composition of fabrics which, in turn, results in difference in transmission behaviour of the sweat solutions. In case of solution type, density plays a prominent role.

In the case of the multi-layered ensembles, solution type contributes to 10%, while seams contribute to 63% and layer type contributes to 22%. Bulging between the fabric layers and seam junction plays a vital role. Liquid transmission behaviour is largely affected by the formation of stitch holes at the junction points.

3.3 Overall Moisture Management Coefficient (OMMC)

The study of overall moisture management coefficient combines three measured attributes of performance, viz the liquid moisture absorption rate on the bottom surface $(MAR)_b$, the difference between absorption rate of top and bottom surface i.e. liquid transport capability expressed in terms of one-way transport capacity (OWTC), and the liquid moisture spreading speed on the bottom surface $(SS)_b$. OMMC is calculated using following equation:

$$OMMC = 0.25(MAR)_b + 0{:}5\ (OWTC) + 0.25\ (SS)_b \quad \ldots (1)$$

In the present case, the other factors such as bottom spreading speed $(SS)_b$, and absorption rate $(MAR)_b$ remain almost negligible. This is due to predominance of P U coated outer layer. Hence, the sum of parameters, viz bottom spreading speed $(SS)_b$ and absorption rate $(MAR)_b$ can be treated as constant (C). The Eq. (1) can be modified as

$$OMMC = C + 0{:}5\ (OWTC) \quad \ldots (2)$$

The Eq. (2) shows that overall moisture management coefficient is linearly dependent on the cross-planar transmittance behaviour of sweat solutions. It is observed that the sweat with higher lactate concentration shows significantly higher OMMC as compared to sweat with lower lactate concentration in the case of the both individual and multi-layer ensemble [Figs 5 (a) & (b)]. It can be ascribed that at higher lactate concentration, gravitational force plays a vulnerable role. This, in turn, will further assist in taking the sweat away from the skin through the layered ensembles. Uni-directional seamed multi-layered spacer fabric exhibits better overall moisture management coefficient as compared to bi-directional seamed spacer ensembles with sweat solution containing higher lactate concentration. Besides, it is also observed that the role of middle layer is significant; as it greatly influences the cross-plane transmittance and in-plane transmittance of both the sweat solutions through the layered ensembles.

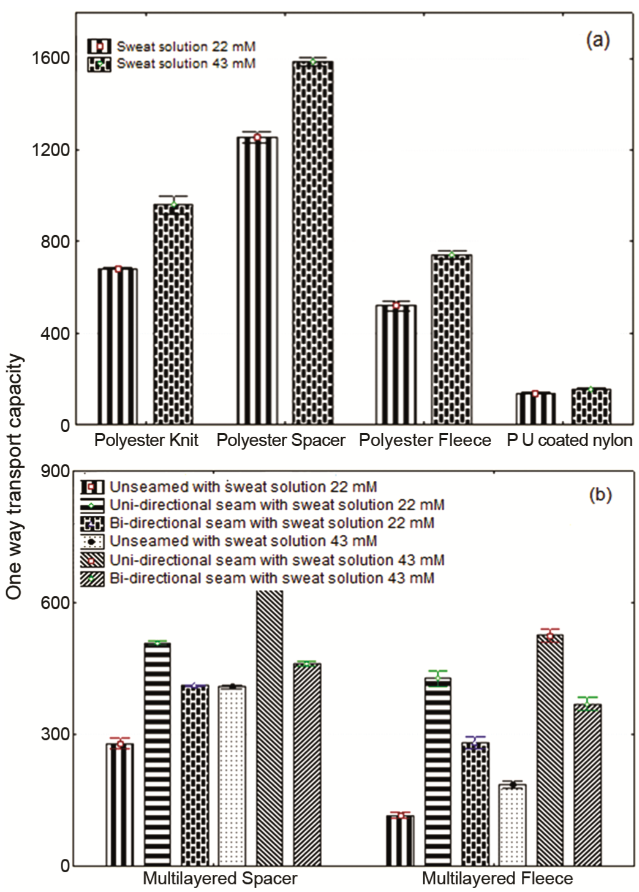

Fig. 5 — OMMC of water and sweat for different fabrics using sweat and water (a) single layer and (b) multi-layered systems

4 Conclusion

The change in the lactate concentration in the sweat solution has a significant influence on the moisture transmission behaviour in liquid form through the fabric ensembles. Further, the fabric structure (constituent layers) behaves differently when tested individually with different sweat solutions. Further, in case of multi-layered ensembles, behaviour of sweat solutions differing in lactate concentration is influenced by several factors, viz material type, formation of stitch hole, nature of pathway created, extent of bulging and the impact of backing layer, presence of outer PU coated layer, and structural composition of middle layers. It is important to mention here that even though practically the layers of multi-layer garment are arranged vertically, but the role of gravity is still there, which is predominant in the present case. Following inferences are drawn:

4.1 Sweat solution containing higher lactate concentration shows lower contact angle, but inspite of that the role of density of sweat solution is more predominant. The sweat solution with higher concentration of lactate (43 mM) shows delayed wetting at the top surface both in case of individual layer and multi-layer fabric ensembles, i.e. it takes longer time to wet the top surface in spite of the lower contact angle made by it.

4.2 Wetting time of solutions in the multi-layered ensemble decreases drastically, even though all the multi-layer ensemble consists of polyester knit fabric at the top surface (wetting time for polyester knit as individual layer is reported as 50-70 s).

4.3 Significant difference is observed in wetting time of both sweat solutions in the case of multi-layered ensembles; highest being observed in the case of uni-directional seamed multi-layered spacer ensembles. Marginal difference is seen in the case of bi-directional stitched multi-layered spacer ensembles.

4.4 Sweat solution with higher lactate concentration shows better moisture management properties through the multi-layered ensembles as it shows higher cross-planar transmission rate as compared to in-plane transmission.

4.5 Uni-directional seamed multi-layered spacer fabric exhibits better overall moisture management coefficient as compared to bi-directional seamed spacer ensembles with sweat solution containing higher lactate concentration.

4.6 From the ANOVA results, it is concluded that in case of individual fabrics, the role of layer is most significant in case of both in-plane and cross-plane transmission behaviour. On the other hand, in the case of the multi-layer ensembles, seams play a predominant role followed by solution type and type of layers. There is least significant in case of in-plane liquid moisture transmission behaviour whereas in case of cross-plane transmission behaviour, seams shows maximum contribution percentage followed by type of layer. Solution type shows least contribution percentage.

4.7 From the present study, one can easily predict the behaviour of liquid moisture transmission, when a person sweat profusely. It can be concluded that in all aspects uni-directional seamed multi-layered ensembles are giving better results.

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