DUJASE Vol. 2(1) 45-51, 2011 (July)

An Investigation to Identify Upper Materials for Optimum Inshoe Climate

Noor Mohammad[1], Dr. Robert Chen[2] and Dr. Patrick Callaghan[3]

[1]*Bangladesh College of Leather Technology, Dhaka, Bangladesh*

[2]*Department of Product and Interior Design, De Montfort University, Leicester, UK.*

[3]*International School of Footwear, Leicester, UK.*

E-mail: noormd458@yahoo.com, RChen1@dmu.ac.uk and ptcllghn@aol.com

Received on 16. 03. 2011. Accepted for publication on 02. 08. 2011

Abstract

We wear shoes to get more comfort and protection for the feet. By researching the effects of in-shoe temperature and relative humidity on comfort we can identify the most appropriate shoe materials. This paper aims to provide a useful and clear understanding of the causes of changing in-shoe climate and so find the most appropriate materials to control it. The in-shoe climate is mainly dependent on the thermal conductivity, water vapour permeability and water vapour absorption properties of the upper materials of the shoe. To devise better solutions, a preliminary literature survey on the hot and cold weather footwear was undertaken. This research helped a lot to select a range of possible materials for practical testing. In designing the shoe there may be an extra interlining material between the upper and lining to increase control over the in-shoe climate. For this reason the thermal conductivity, water vapour permeability and water absorption properties of a range of upper, lining and interlining materials have been measured. Finally a prototype shoe upper was made using the materials found to be most suitable to show the design development. After comparative analysis of the test results, some materials were found to be better than others for controlling the in-shoe climate. Among the materials tested, aniline finished leather and milled-dyed crust was found to be best for lining materials. Polyester fabric containing a small amount viscose rayon was found to be the best interlining material. Using these materials one prototype shoe upper was made which should be the most effective for keeping the feet warm in a cold climate and eliminating perspiration in a hot climate. The interlining material will give extra warmth in a cold climate but will not affect the transmission of the perspiration in a hot climate. To confirm the suitability of the chosen materials, a pair of shoes should be made up and wear tested using humidity and temperature sensors.

Keywords : Inshoe climate, shoe materials, thermal conductivity, water vapour permeability, water vapour absorption, interlining, aniline finished leather, milled-dyed crust leather, polyester fabric.

1. Introduction

There are three main purposes for footwear. These are :

a. Foot protection
b. Comfort
c. Fashion

"The comfort footwear is big business and has become one of the main considerations when buying shoes" (SATRA Bulletin, February 1998, p-17). The comfort of the shoe is largely dependent on material properties and design. From a thermal perspective, the primary function of the shoe is to keep the feet warm in cold climates and to reduce perspiration in hot climates. "A human is considered to be comfortable when the skin temperature is between 33^0 and 35^0 C and there is no deposit of liquid sweat on the skin, although the foot can still feel reasonably comfortable down to 20^0 C" (SATRA Bulletin, November, 1998, p-2).

In wearing the shoe there is a certain amount of rubbing occurs between the inside surface of the shoe and the skin or hose material. This generates a lot of heat and if the outside temperature is lower than the in-shoe temperature, then the inside temperature tends to decrease and the feet become cold and feel uncomfortable.

On the other hand, when the outside and as well as inside temperature of the shoe is high, then a lot of 'sensible' perspiration is produced by the feet. This inside perspiration will also cause discomfort. To overcome these problems in both hot and cold weather, it is necessary for the shoe designer to control in-shoe climate by selecting the most suitable materials together with an appropriate shoe design.

People experience discomfort if they are exposed to extremes of temperature and moisture. Preventing external moisture from contacting the skin is normally accomplished by use of 'waterproof' clothing and footwear. The problem under investigation here is how to protect people from extremes of external temperature, and allow internal moisture generated by the body (as perspiration) to escape while still preventing access by external liquid moisture. This property is called **Water Vapour Permeability (WVP)**.

A single water molecule is approximately 1/5,000,000 mm in diameter. Even a small liquid water droplet contains many billions of water molecules clumped together and held by surface tension forces. Water vapour molecules have more energy and exist singly or in small groups that can pass through much smaller holes than liquid water (Fig.1). One way to enhance WVP is by creating an interconnected system of 'pores' in an otherwise water-repellant (hydrophobic) material that are in a suitable size range. For example the Gore Tex™ 'Teflon' film contains over 1 billion pores/cm^2, each around 1/20,000 the size of a water droplet.

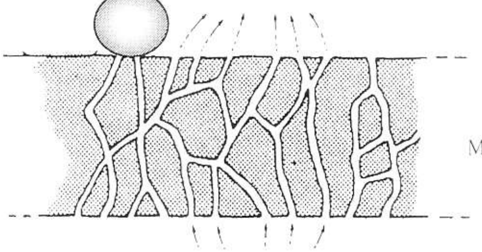


Fig. 1: water vapour molecules are small enough to pass through the 'pores to the

The ability of the material to insulate from extremes of temperature is measured by its **Thermal Conductivity**.

The rate at which heat and moisture can pass through a material also depends on the difference in temperature and relative humidity between the inside and the outside of the material.

Temperature and humidity conditions inside the shoe during wear is called in-shoe climate. For making closed styles of comfort shoe, especially those with a higher topline, the controlling of this climate is one of the main requirements. To do this, we need to identify and use the appropriate shoe materials that have low heat conductivity and a high water vapour permeability combined with low absorption properties. Besides the selection of materials it is also essential to develop the shoe design.

From related research work of various scientists of SATRA, UK we know the effects of temperature and humidity on foot comfort during wear; and so understand the types of materials that might be suitable for hot and cold weather footwear. Then it is necessary to identify which of these materials are the most suitable by practical testing and produce a suitable upper construction. The developed shoe upper using the selected materials should keep the feet warm in a cold climate and disperse perspiration better in a hot climate during wear.

2. Experimental

For the primary research work, two Footwear industry-standard tests were carried out to identify the appropriate shoe materials. The tests are SATRA Permeability/Absorption (P/A) test and Lee's Thermal Conductivity test.

2.1 Water Vapour Permeability and Absorption test process

Water vapour permeability (WVP) is the ability of a material to transmit water from one side to the other in the form of vapour. Water vapour absorption (WVA) refers to how much of that vapour is retained by absorption within the material structure. WVP in shoe upper materials helps in the dispersal of perspiration and makes an important contribution to foot comfort and hygiene. The rate at which moisture passes through permeable materials is controlled by the difference in temperature and humidity between the two sides of the material.

Another factor influencing a wearers feeling of comfort is the amount of water retained by hose material next to the skin. Although the hose has little effect on WVP, the amount of moisture it has absorbed during the test indicates how damp the feet might feel after a period of wear. WVA by hose is likely to be high if water absorption and WVP in the outer are both low.

In the SATRA Permeability/Absorption (P/A) method used here (Fig.2a and 2b), upper material is combined with standard hose material and tested under realistic conditions of humidity and temperature.

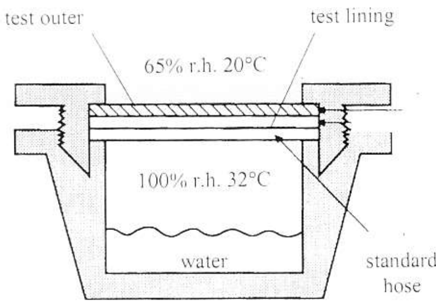


Fig. 2a: Cup used in Permeability/Absorption method.

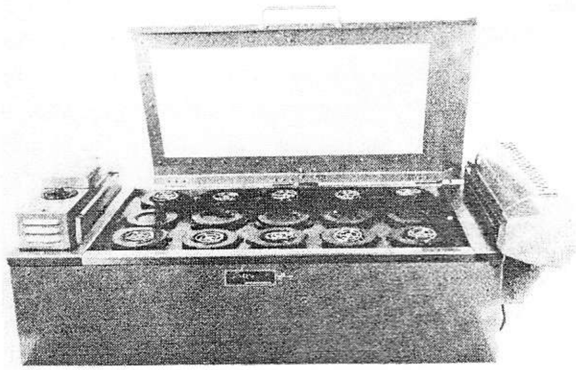


Fig. 2b: SATRA Permeability/Absorption Apparatus

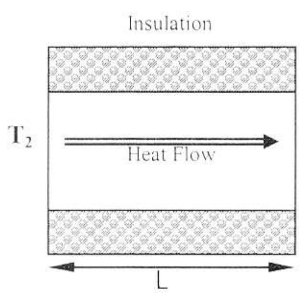
The P/A test can also be carried out with lining material included. To compare the WVP of linings, it necessary to use a standard outer leather of high WVP (6 mg/cm^2/hr), e.g. aniline calf.

2.2 Thermal Conductivity test process

The ability of a shoe material to resist the passage of heat is important to foot comfort when the weather is cold. As a general rule, non metallic materials are much poorer conductors of heat (and electricity) than metals. i.e. They have low thermal conductivities and are therefore often referred to as heat insulators. The method of measurement described here is suitable for discriminating between materials of low conductivity only.

The simplest theoretical case for study is where the temperature difference between the ends of a uniform bar of material is kept constant, and heat loss from the sides of the bar is prevented. The rate of heat transfer (J/S or W) from the hotter end to the cooler end then depends on:-

a. The cross- sectional area (A) of the bar (m^2).
b. The distance (L) between the ends of the bar (m).
c. The temperature drop (T_2-T_1) between the ends of the bar (^0C).
d. The thermal conductivity (λ) of the material ($W/m/^0C$).



$$\text{Rate of heat flow} = \frac{\lambda \cdot A \cdot (T_2 - T_1)}{L}$$

In practice, significant heat loss (mainly by radiation) occurs from the sides of the bar and this is best estimated from measurements of surface temperature and exposed area, rather than attempting to prevent it occurring. The 'Lees Discs' equipment (Fig.3a and 3b) was used in these tests.

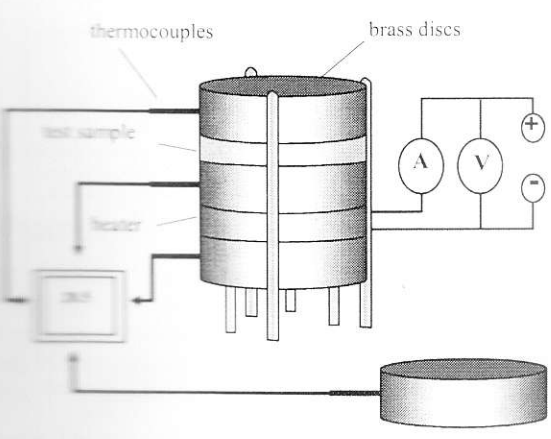


Fig. 3a: Mechanism used in Lees Discs' equipment

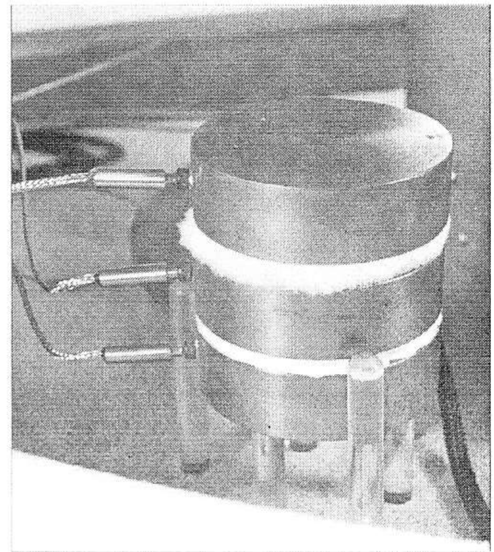


Fig. 3b: Lees Discs' equipment

3. Comparative Results

In this research work, it was not possible to control the external relative humidity and room temperature during testing. Consequently the results might be slightly higher for relative humidity and lower for thermal conductivity than would be found under standard conditions.

The standard condition is 65% relative humidity and 20^0C room temperature. The actual test conditions were 45% r.h. and 22 - 24^0C room temperature.

These conditions resulted from carrying out the tests in an area protected from draughts within a laboratory serviced by the buildings re-cycled air circulation system. We believe that the non-standard conditions would make no difference to the ranking of the materials tested.

4. Selection of Materials

If the footwear is to be used mainly outdoor, then the outer part of the upper material, if not waterproof, should at least 'shower resistant' so that external liquid moisture (rain or snow) is not a direct source of discomfort. For mainly indoor use, water-resistance is less important.

Both natural (leather, cotton, etc.) and synthetic (PU or PVC coated fabric, etc.) materials can be used for making the upper. Most pigment-finished leathers are reasonably showerproof. Aniline leathers, while highly permeable, are more sensitive to water. Modern PU-coated fabrics are waterproof, but have some permeability. PVC-coated fabrics for outers are waterproof but have no permeability. PVC films can be made porous for use in a lining material.

To make a comfort shoe for use both in hot and cold climates, we need to select materials or material combinations that have high permeability and low thermal conductivity so as to reduce the loss of heat from inside the shoe in cold weather and absorb and transmit perspiration from the feet in hot weather.

Selection is based on the measurements of water vapour permeability/absorption and the thermal conductivity of a wide range of upper, lining and interlining materials currently available to shoe and clothing manufacturers. Analysis of results from the two tests should allow the selection of materials with the optimum balance of properties for controlling in-shoe climate.

Table 1: Upper Materials
Water vapour permeability/absorption and thermal conductivity of selected upper materials

Material No.	Type of Material	Thickness (mm)	WVP ($mg/cm^2/hr$)	WVA (mg/cm^2) after 300 min	WVA of Standard Hose (mg/cm^2) after 300 min	Thermal Conductivity (W/m/°C)
U-01	Aniline Finished Leather	1.2	10.241	1.213	0.929	0.066181
U-02	Semi- Aniline Finished Leather	1.2	1.022	18.966	5.841	0.068461
U-03	PU coated non-woven fabric	1.1	0.895	12.178	4.172	0.058855
U-04	Corrected Grain Leather	1.25	3.772	10.242	2.825	0.072823
U-05	Patent Leather	1.3	0.557	20.712	3.85	0.062784
U-06	Waterproof Leather	1.45	0.876	19.517	2.617	0.079080
U-07	Dyed Finished Leather	1.35	6.726	4.096	0.739	0.075155
U-08	PVC coated woven fabric	0.8	0.244	3.262	16.766	
U-09	PU coated non-woven fabric	1.1	8.277	0.872	0.587	
U-10	Corrected and Dyed Finished Leather	1.1	9.380	2.029	1.175	

Table 2: Lining Materials
Water vapour permeability/absorption and thermal conductivity of selected lining materials

Material No.	Type of Material	Thickness (mm)	WVP ($mg/cm^2/hr$)	WVA (mg/cm^2) after 300 min	WVA of Standard Hose (mg/cm^2) after 300 min	Thermal Conductivity (W/m/°C)
L-01	Leather	0.85	1.542	18.246	4.134	0.056958
L-02	PU coated woven fabric	0.70	2.942	4.874	4.362	
L-03	Leather	0.80	7.362	3.224	0.966	
L-04	Combined woven fabric	0.70	1.484	10.602	6.771	
L-05	Leather	0.80	3.846	7.453	3.074	
L-06	Leather	0.80	4.926	7.738	1.195	
L-07	Leather	0.95	11.006	0.625	0.682	
L-08	Leather	1.1	11.821	0.682	0.493	

Table 3: Interlining Materials
Thermal conductivity of interlining materials

Material No.	Type of Material	Thickness (mm)	Thermal Conductivity (W/m/°C)
IL-01	Non-woven Micro fibre with resin bonding agent with woven fabric backing	1.2	0.046505
IL-02	Woven Cotton	1.1	0.068499
IL-03	Knitted Nylon	2.2	0.052272
IL-04	Combined woven fabric (top- cotton and bottom- viscose rayon)	1.1	0.040080
IL-05	Woven Cotton	0.8	0.066124
IL-06	Mixed material (top-EVA and bottom-knitted cotton fabric)	2.25	0.051980
IL-07	Combined knitted fabric (Mixed wool and acrylic fibre)	3.5	0.027762
IL-08	Woven Nylon	0.83	0.042292
IL-09	Shearling (Fur skin)	2.2	0.024576
IL-10	Knitted Wool	2.75	0.042484
IL-11	Knitted Polyester	1.7	0.023656
IL-12	Gore Tex™	1.8	0.034214
IL-13	Knitted Polyester	2.55	0.054740
IL-14	Material of combined Polyester and viscose rayon	0.8	0.014007
IL-15	Loose knitted Polyester (with small amount of underneath)	1.3	0.025257

Table 4: Combined upper and lining materials
Thermal conductivity of combined upper and lining materials

Material No.	Type of Material	Thickness (mm)	Thermal Conductivity (W/m/°C)
U-01 and L-01	Upper- Leather (Dye finished) Lining- Leather (Dyed and coated finished)	2.15	0.087117

Table 5: Interlining with same Upper and Lining materials
Thermal conductivity of selected interlinings with same upper lining materials

Material No.	Type of Material	Thickness (mm)	Thermal Conductivity (W/m/°C)
IL-01	Non-woven micro fibre with resin bonding agent. Woven fabric backing	3.4	0.081306
IL-02	Woven Cotton	3.2	0.079391
IL-03	Knitted Nylon	4.8	0.067251
IL-04	Combined woven fabric. (Top-cotton and Bottom-viscose rayon)	3.85	0.073486
IL-15	Loose knitted Polyester (with small amount of cotton on bottom part)	3.8	0.056374

4.1 Upper Material

To identify the most permeable material for the shoe outer, various types of leather (e.g. aniline finished (dye finished), heavy pigment coated, corrected grain, patent finish, water proof, coated splits); and synthetic materials (e.g. PU coated fabric, PVC coated fabric) were tested.

Among the materials, the Aniline finished leather (sample U-01) is most water vapour permeable (10.241 mg/cm^2/hr). It is not very water resistant, but can be used successfully as upper material. According to the SATRA P/A test method, if the water vapour permeability of a test material is higher than 5.0, then it is classed as having 'very good' permeability for footwear. The materials found to be very permeable included the corrected grain leather (U-10, 9.380 mg/cm^2/hr) and PU coated non woven fabric (U-09, 8.277 mg/cm^2/hr). The corrected grain leather can also be suitable material for the shoe upper but in the case of PU coated non woven fabric, its large pore structure makes it less suitable than the sample no. U-01, because it is not water resistant.

If we consider the thermal conductivity of upper materials then it can be seen that the PU coated non woven fabric (sample no. U-03) has the lowest conductivity of the upper materials tested. This value is 0.059 W/m/^{0}C. Its thickness is suitable for shoe upper. This material, however cannot be used as a shoe upper for controlling the in-shoe climate, because it's water vapour permeability is very low (0.895 mg/cm^2/hr).

On the other hand the material no. U-01 has a low conductivity- 0.069 W/m/^{0}C. This material-1 absorbs comparatively little water vapour compared to the other materials tested. The standard hose also absorbed less water; so the material will not absorb much water during wearing the shoe and will give comfort to the wearer.

In the SATRA P/A test, Water Vapour Absorption of standard hose material after 265 minutes represents the amount of perspiration that is likely to be retained in footwear after 8 hours of the continuous wear. As a general rule, WVA should be less than 75 mg (about 3 mg/cm^2) for acceptable comfort. However if materials dry out quickly between periods of wear, a higher value than this can be accepted.

The WVA of the material no. U-01 is 1.213 mg/cm^2 and for standard hose is 0.929 mg/cm^2 which is lower than 3 mg/cm^2.

Conclusion:- For controlling the in-shoe climate, the sample no. U-01 (Leather – Aniline finished) is very good upper material for both in hot and cold weather.

4.2 Lining Material

Beside the upper material, the lining material should be permeable and less water absorbent. If it absorbs more water and the water vapour cannot move then it causes more discomfort to the wearer, because the lining is closer to the skin. Consequently it is necessary to identify the most permeable lining material. Normally it should be thinner than upper; so it will not add much strength to the shoe. A range of materials were tested for water vapour permeability and absorption to find the most permeable lining material. These include leather (dyed and coated, dyed crust, natural white crust, milled and dyed crust), PU coated woven fabric, combined (cotton and viscose rayon) woven fabric, etc.

Among the materials, Material no. L-0 8 was found to be the most water vapour permeable (11.821 mg/cm^2/hr). It is milled and dyed crust. Material no. L-07 also had high permeability (11.006 mg/cm^2/hr). This is a natural white crust. Both materials retain less water (Material L-07: 0.625 mg/cm^2 and material L-08: 0.682 mg/cm^2). In the case of material L-08 the standard hose retained the least amount water (0.493 mg/cm^2) of all the lining materials tested; which is much less than the acceptable range for comfort (acceptable range up to 3 mg/cm^2).

Conclusion: It is clear that to control the in-shoe climate, material no. L-0 8 which is milled and dyed crust is the most suitable for use as a lining material.

4.3 Interlining Material

To control the in-shoe climate we need to use the upper and lining material which are highly water-vapour permeable but have low thermal conductivity. To get these two properties in the same material is very difficult. Sometimes we get them by losing other properties like strength. Often normal upper and lining materials are not good at reducing heat transfer from skin to outside in cold weather. If we use an extra material between the upper and lining as interlining in higher top-lined footwear, then it is possible to keep the feet warm in cold weather. To select the interlining material, we can look to textile materials which are worn in cold weather as garments. Most of these textile materials are porous and there fore permeable to water vapour. These pores can hold air, which is good insulator for heat.

To identify the appropriate permeable interlining for keeping the feet warm in cold climate, the following materials were tested:

- Micro fibre with resin bonding agent and back side cotton,
- Cotton (woven structure),
- Nylon (knitted structure),
- Combined woven fabric (cotton and viscose rayon),
- Mixed material (top- EVA and bottom – knitted cotton fabric),
- Combined knitted fabric (wool and acrylic fibre),
- Shearling (wool skin from sheep which have been sheared before slaughter. The length of wool is quite short.),
- Wool (knitted structure),
- Polyester (knitted structure) with small amount of cotton,
- Polyester (knitted structure) Gore Tex™,
- Combined material (polyester and viscose rayon).

Among the materials tested, sample no.IL-14: Combined fabrics (polyester and viscose rayon) had the lowest thermal conductivity (0.014 W/m/^{0}C). One problem with this material, is that it has a high viscose rayon content which will absorb and hold water strongly; and so will increase the thermal conductivity in wet conditions. Another sample no. IL- 15: polyester (with a small amount of cotton), was also found to have a low heat conductivity (0.025 W/m/^{0}C). This material is very light in weight and will not increase the weight of footwear very much. Due to its open structure, it will give the shoe a cushioning effect for added comfort.

When the thermal conductivity of combined upper (material no. U-01) and lining (material no. L-01) material is measured it was 0.089 W/m/^{0}C. When also combined with the interlining material (material no. IL-15), then the overall thermal conductivity was 0.056 W/m/^{0}C. So the interlining reduces the thermal conductivity of the shoe outer which will keep the feet warmer in cold climate. Other interlinings tested in combination with the same upper and lining did not reduce thermal conductivity as much as sample no. IL-15.

Conclusion: Sample no. IL-15 (Loose knitted structure of polyester with little mount of cotton in the bottom) is the best interlining material in the range tested.

5. General Discussion

The purpose of this research was to investigate in-shoe climate in higher toplined footwear and devise better solutions for controlling it. From the literature, various opinions about how this may be done were considered. Some researchers have tried, with limited success, to find an upper material that controls both thermal conductivity and water vapour permeability but also provide resistance to external water. Some materials can reduce the heat loss from the shoe but are unable to transmit enough moisture through the material. On the other hand some materials have high permeability but are not suitable for a shoe upper due to lack of water resistance or structural weaknesses. The aim of the current research was to examine a range of existing shoe upper materials to find which had the best WVP with acceptable level of water resistance and strength, and which the lowest thermal conductivity. These materials would then be combined to make the shoe upper.

Normally a shoe upper contains upper (top most) part and lining. To control the in-shoe climate, the shoe upper is the most responsible part. This part should have high water vapour permeability but less thermal conductivity. Separately a range of materials is tested and selected leather upper and lining materials of high water vapour permeability with low thermal conductivity. Then combined the upper and lining as shoe upper and measured the WVP and thermal conductivity. A range of interlining materials is tested for thermal conductivity and WVP. The interlining materials in combinations of same upper and lining materials are also tested. These scientific results prove that the extra interlining reduce the thermal conductivity of the shoe upper. This material will not affect the permeability due to its porous and hydrophobic nature.

In the primary research a range of material (leather, cotton, synthetic) was collected and two scientific tests –WVP/A and TC were tested for upper, lining and interlining materials. The composition and structure of each material was determined by microscopic examination and flame tests in the laboratory.

In the case of water vapour permeability/absorption tests it is essential to control the humidity and temperature. The relative humidity should be 65% and the temperature should be 20^0C, but in the research time it was not possible to control. During working the room temperature varied from 22^0C to 25^0C and the relative humidity was 40-45%. This variation might affect the original results because the water vapour permeability and thermal conductivity are mostly affected by temperature and relative humidity. The thermal conductivity of the material is increased with higher moisture contents. On the other hand outside lower humidity increases the permeability of the materials.

6. Conclusions and Recommendations:

From the tests carried out on range of materials it can be concluded that leather makes a better outer and lining material than PU coated or PVC coated fabrics for controlling the in-shoe climate (shoe inside temperature, humidity). The leather is porous, so it is water vapour permeable for removing the perspiration from the shoe inside. On the other hand the pores of the leather can hold air that can be used as a heat insulator in cold weather for keeping the feet warm. If the leather is heavily coated with binder and pigment, then its permeability is reduced to levels like those found with coated fabrics. Aniline finished leather can control the in-shoe climate most successfully. To increase the heat insulating property of the shoe for reducing the heat loss, we need to use the polyester fabric (knitted open structure) between the upper and lining material. This interlining has the added advantages of not affecting the overall water vapour permeability of the shoe upper. The higher toplined footwear of this upper should control the in-shoe climate both in hot and cold weather.

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