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Thermo-physiological Comfort Properties of Suede Leathers for Footwear and Apparel

Fazlı AKYÜZ [1], Urana DANDAR [2], Nilgün ÖZDİL [2], Nuray Olcay IŞIK EMEKSİZ [3], Ahmet ASLAN [2], Meruyert KAYGUSUZ [4] *

[1] *Istanbul University-Cerrahpaşa, Vocational School of Technical Sciences, Department of Environmental Protection Technologies, 34500, Büyükçekmece, Istanbul, Türkiye*
[2] *Ege University, Engineering Faculty, Leather Engineering Department, 35100, Bornova, Izmir, Türkiye*
[3] *Tekirdağ Namık Kemal University, Çorlu Vocational School, Department of Textile, Apparel, Footwear and Leather, 59860, Çorlu, Tekirdağ, Türkiye*
[4] *Isparta University of Applied Sciences, Vocational School of Technical Sciences, Department of Textile, Apparel, Footwear and Leather, 32100, Çünür, Isparta, Türkiye*

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Thermo-physiological comfort has become an essential quality parameter for footwear and apparel materials, particularly in natural leather, where heat, air, and moisture regulation directly affect wearability. Among these, suede leathers exhibit distinctive comfort behaviour due to their napped, open-pore structure. This study aimed to compare the thermo-physiological comfort properties of suede leather for footwear and apparel, focusing on physical strength, air and water vapour permeability, and thermal performance. Physical-mechanical properties of suede leathers were evaluated according to International Organization for Standardization (ISO) standards (tensile strength, elongation, tear load), air and water vapour permeability, and thermal parameters (conductivity, resistance, absorptivity) were measured. Apparel suede exhibited significantly higher tensile strength and elongation, reflecting flexible collagen structures suited to body movement. They also exhibited greater air and water vapour permeability, supporting moisture transfer and breathability in garments. Suede footwear demonstrated higher thermal resistance and absorptivity, providing insulation and a cooler tactile sensation, functional for foot protection and maintaining microclimate stability. These findings highlight the application-specific optimization of suede leathers: apparel suede is preferred for flexibility, softness, and breathability, whereas footwear suede emphasizes insulation, durability, and tactile cooling. The study offers valuable guidance for material selection in design and manufacturing, bridging scientific evaluation with consumer-driven comfort needs.

Keywords: air-permeability, footwear, garment, leather materials, suede, thermal comfort.

1. INTRODUCTION

Comfort has become a central criterion in evaluating footwear and apparel materials, driven by consumer demand for products that support health, performance, and overall well-being. Beyond durability, fashion, and aesthetics, modern users expect materials to provide thermal regulation, breathability, and moisture management during daily wear. For natural leathers, especially those used in shoes and garments, thermo-physiological comfort has emerged as a decisive quality factor [1 – 4].

Thermo-physiological comfort refers to a material's capacity to regulate the exchange of heat, moisture, and air between the human body and the environment. Parameters such as thermal conductivity, thermal resistance, thermal absorptivity, air permeability, and water vapour permeability determine whether the wearer experiences a balanced microclimate or discomfort caused by overheating, sweating, or excessive moisture retention [3, 5, 6].

Previous studies have provided insights into related aspects. The thermo-physiological comfort properties of garment leathers tanned with different tanning agents (chrome, zirconium, glutaraldehyde, phosphonium, and vegetable tannin) were investigated, and it was found that chrome tanning produced the highest thermal conductivity and the lowest thermal resistance, whereas glutaraldehyde-tanned leathers showed the highest thermal resistance. Zirconium tanning resulted in superior water vapour permeability, whereas vegetable tannins increased thermal absorptivity, producing a cooler tactile sensation [7]. Similarly, the effect of finishing with aniline, pigment, and patent finishes on footwear comfort properties was examined, showing that finishing reduced water vapour and air permeability [8]. The findings indicate that both tanning and post-tanning methods affect the thermo-physiological behaviour of leather [9]. It was also reported that, while finishing reduces the monolayer size and increases moisture binding-energy constants, fatliquoring decreases the maximum moisture uptake and hysteresis, thereby also reducing the monolayer size [10].

The thermal insulation of various leather clothing was determined by measuring the heat input required to maintain equilibrium between the cold-chamber and heat-source temperatures. It was found that the more organized and dense fibre packing in leather provides better thermal

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[*] Corresponding author: M. Kaygusuz
E-mail: *meruyertkaygusuz@isparta.edu.tr*

insulation [11]. It was also concluded that when natural leather items are used in demi-season conditions, their thermal and water vapour resistances are comparable to conventional levels, and air resistance increases significantly without a change in comfort [12].

Among the diverse types of leather, suede presents distinctive characteristics that make it particularly relevant for comfort studies. Produced by sanding the flesh side or split layer of hides, suede has a napped, open-pore surface that enhances breathability and moisture transfer compared to smooth, grain leather [13]. This porous structure supports air circulation, moisture wicking, and insulation, properties that make suede attractive for transitional garments and casual footwear [14]. However, footwear suede typically requires higher structural durability and insulation, while garment suede emphasizes softness, flexibility, and tactile warmth. These contrasting requirements suggest that their thermo-physiological performance may differ, yet systematic comparisons remain scarce.

Building on this ground, the present study addresses a clear research gap by focusing specifically on the thermo-physiological comfort of suede leather for footwear and apparel. This study aims to compare the thermo-physiological comfort characteristics through standardized measurements of thermal conductivity, thermal absorptivity, and thermal resistance. The findings will offer valuable insights for designers and manufacturers in both the footwear and apparel sectors, guiding material selection based on application-specific comfort requirements.

2. MATERIALS AND METHODS

2.1. Materials

A total of nine footwear suede leathers and six apparel suede leathers were used in this study. The leathers were produced from goat skin and supplied by a commercial tannery in Uşak Province, Türkiye. The suede leathers for apparel were processed using the conventional chromium tanning, whereas the leathers for footwear were processed by the wet-white tanning method. They were produced by adjusting the thickness differently through the shaving process. While only the back side of shoe leathers is shaved to equalise the thickness, the entire surface of garment leathers is shaved. Moreover, to make them softer, a sanding process is applied to the back side of garment leathers as well. The leather samples were encoded as suede for footwear (SFW) and for apparel (AS). Before testing, all samples were conditioned according to TS EN ISO 2419:2012 [15] at a controlled temperature of 23 ± 2 °C and relative humidity of 50 ± 5 %. The test specimens were then prepared from the designated sampling areas as defined in TS EN ISO 2418:2017 [16], ensuring a standardized and reproducible evaluation of the physical and thermo-physiological properties.

2.2. Methods

Measurements of leather thickness were performed following TS 4117 EN ISO 2589:2006, and water vapour permeability was conducted in line with TS EN ISO 14268:2014 [17, 18]. Tensile strength was determined following TS EN ISO 3376:2020, and tear strength was measured according to TS EN ISO 3377-1:2020 [19, 20]. Air permeability was mesured using a Devotrans DVT-HG air permeability tester (Devotrans, Istanbul, Türkiye). Thermal properties (thermal conductivity, thermal resistance, and thermal absorptivity) were evaluated using an Alambeta device (Sensora Instruments, Liberec, Czech Republic) under both steady-state and transient conditions, using a contact pressure of 200 Pa. All measurements were performed in triplicate, and the results are presented as mean values.

Statistical analyses were performed using SPSS (IBM Corp., Armonk, NY, USA). Independent-samples t-tests were applied to assess differences between footwear and apparel suede leathers. Statistical significance was set at $p \leq 0.05$. Parameters with p-values above this threshold were considered statistically non-significant. Surface morphology was examined using a Tabletop Scanning Electron Microscope (TSEM, TM3030, Hitachi High-Technologies, Tokyo, Japan).

3. RESULTS AND DISCUSSION

3.1. Physico-mechanical properties of the suede leathers

The physical and mechanical properties of the suede leathers are presented in Table 1. The results, expressed as mean ± SD ($n = 3$) with corresponding p-values from independent t-tests, revealed clear distinctions between suede leathers intended for footwear (SFW) and those designed for apparel (AS). The tensile strength and elongation show an inverse proportional change depending on the variation in thickness. The tensile strength of the suede leathers demonstrated statistically significant differences between the SFW and AS groups (Table 1). Apparel suedes recorded higher mean tensile strength values (AS3: 27.91 ± 0.72 N/mm^2; AS4: 24.15 ± 0.66 N/mm^2) compared with footwear samples (SFW1: 18.12 ± 0.54, SFW2: 17.71 ± 0.61; SFW3: 19.58 ± 0.48 N/mm^2, $p < 0.05$).

Table 1. Physico-mechanical properties of the suede leathers

Sample	Thickness, mm	Tensile strength, N/mm^2	Elongation, %	Tear load, N	p-value, vs. AS
SFW1	1.29	18.12 ± 0.54^{a}	56.63 ± 1.92^{a}	23.48 ± 0.87^{a}	< 0.05
SFW2	1.17	17.71 ± 0.61^{a}	52.89 ± 2.05^{a}	25.29 ± 0.75^{a}	< 0.05
SFW3	1.13	19.58 ± 0.48^{a}	67.11 ± 1.64^{b}	30.30 ± 0.92^{b}	< 0.05
AS3	0.84	27.91 ± 0.72^{b}	72.05 ± 1.21^{c}	30.32 ± 0.89^{b}	Reference
AS4	0.80	24.15 ± 0.66^{b}	76.72 ± 1.17^{c}	31.46 ± 0.94^{b}	Reference
Values with different superscript letters within the same column differ significantly ($p \leq 0.05$)					

The difference in the tensile strength of the suede leathers obtained from the same origin can be explained by the processing with the different tanning methods. The superior performance of apparel suedes is attributed to the chromium tanning method, with which leathers are characterized by denser and more uniformly oriented collagen fibres, thereby enhancing their durability. In contrast, footwear suedes, tanned with wet-white, possess looser fibre structures and porosity that minimize their strength. Similar trends have been documented, showing that tanning systems modulate collagen bonding density [7] and that tighter fibre networks increase tensile resistance [21]. These findings confirm that apparel suedes are structurally optimized for garment durability without excessive bulk.

Elongation at break further distinguished the two categories. Apparel suedes exhibited significantly higher extensibility (AS3: 72.05 ± 1.21 %; AS4: 76.72 ± 1.17 %) relative to footwear suedes (SFW1: 56.63 ± 1.92 %; SFW2: 52.89 ± 2.05 %; SFW3: 67.11 ± 1.64 %, $p < 0.05$). High elongation is advantageous in apparel, as garments must conform to dynamic body movements while retaining shape. Structurally, increased elongation is associated with finer fibre bundles, higher interfibrillar mobility, and retanning processes that enhance flexibility [22, 23]. Footwear suedes, conversely, often undergo treatments to increase stiffness, thereby reducing extensibility but improving dimensional stability for shoe uppers. Recent work on sheep garment leather demonstrated that reduced rigidity and optimized thickness improved drape quality and wearer comfort, highlighting the role of extensibility in garment performance [24]. Hence, apparel suedes combine tensile integrity with elasticity, making them well-suited for functional comfort in clothing.

Tear strength values showed more overlap between categories but still revealed notable differences. Apparel suedes demonstrated slightly higher resistance (AS3: 30.32 ± 0.89 N; AS4: 31.46 ± 0.94 N) compared with footwear samples (SFW1: 23.48 ± 0.87 N; SFW2: 25.29 ± 0.75 N; SFW3: 30.30 ± 0.92 N, $p < 0.05$). Interestingly, SFW3 exhibited tear strength comparable to apparel suedes, suggesting that leather properties can be affected by factors such as species origin, breeding, age, and processing method. Tear strength reflects the resistance of collagen fibres to separation at stress concentration points [25]. Variability among footwear samples likely arises from splitting thickness and buffing intensity, both of which modify fibre continuity and, thus, tear propagation behaviour. Similar effects have been observed during chrome tanning processes, where splitting significantly influenced tear resistance [26]. Although the apparel suedes generally slightly outperformed the footwear samples, both categories displayed sufficient tear resistance for their respective applications, garments emphasizing balanced durability and flexibility, while footwear prioritizes stability, surface properties, and breathability.

To correctly interpret the results, it should be noted that suede leathers used for footwear and apparel differ in their structural characteristics (thickness, density, and morphology) due to their intended end-use. These structural variations directly influence moisture and heat transfer behaviour and therefore play a critical role in determining thermo-physiological comfort performance. Therefore, the observed variations in performance parameters are discussed in relation to these product-type-specific characteristics.

3.2. Air and water vapour permeability of the suede leathers

The regulation of air and moisture transfer through leather is a key factor influencing thermo-physiological comfort. Fig. 1 illustrates the air permeability and water vapour permeability of suede leathers intended for footwear (SFW) and apparel (AS), expressed as mean ± SD ($n = 3$). Significant differences were observed between the two groups ($p \leq 0.05$), with the apparel suedes demonstrating consistently higher permeability values.

The apparel groups (AS3, AS4) exhibited markedly greater air permeability compared to the footwear samples (SFW1–3). This outcome aligns with their more open-pore surface structure, which facilitates airflow through the collagen network. In contrast, the footwear suedes demonstrated lower permeability, reflecting grain structure and finishing treatments that partially occlude surface pores to enhance durability. Similar observations were reported by Sundar and Muralidharan [27] and Akalović et al. [28], who demonstrated that increased porosity in leather structures significantly enhances water vapour and air transmission compared with compact grain leathers. More recent studies confirm that material selection strongly governs air and moisture transmission, a factor essential for optimizing end-use comfort properties [6, 29, 30].

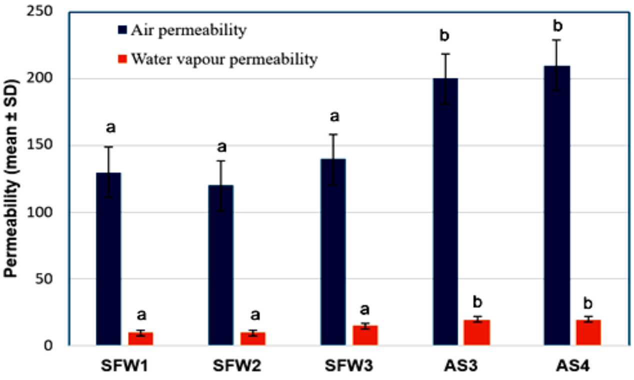


Fig. 1. Air and water vapour permeability of suede leathers used for footwear (SFW) and apparel (AS)

The apparel leathers also demonstrated significantly higher water vapour permeability, indicating superior ability to transfer perspiration away from the body. This property is critical in garments, as insufficient vapour transmission can lead to moisture accumulation, skin irritation, and reduced thermal comfort. The footwear suedes recorded lower values, reflecting the need to balance moisture management with thermal insulation in shoe uppers. These results align with Li et al. [31] and Liu et al. [1], who showed that high vapour permeability in shoe materials reduces plantar skin temperature and relative humidity, improving comfort during extended wear. Additionally, it was observed that finishing layers can significantly reduce vapour transfer by blocking capillary pathways [8], which may explain the comparatively restricted permeability of footwear suedes. The combined results confirm that apparel suedes are structurally and functionally tailored for higher air and vapour permeability, promoting breathability, softness, and wearer comfort.

By contrast, footwear suedes, while less permeable, maintain adequate performance levels but prioritize stiffness, strength, and microclimate insulation – properties critical to protecting the foot under mechanical and thermal stresses. These findings reinforce the application-specific optimization of suede leathers and underscore the importance of considering both mechanical and transport properties in material selection for comfort-driven design.

Since the interaction of heat and moisture transfer directly influences the wearer's perception of comfort, it is essential to evaluate thermal properties in conjunction with permeability. Therefore, the following section focuses on the thermal conductivity, resistance, and absorptivity of suede leathers to provide an integrated understanding of thermo-physiological comfort across application contexts.

3.3. Thermal comfort of the suede leathers

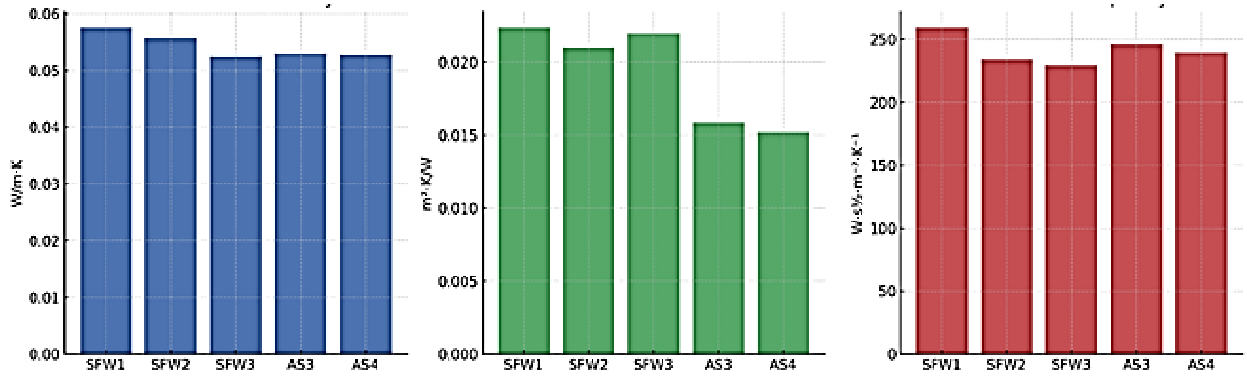
Thermal comfort represents a critical determinant of wearability, as it reflects the balance of heat retention, dissipation, and tactile sensation experienced by the user. The thermo-physiological behaviour of suede leathers was assessed in terms of thermal conductivity, resistance, and absorptivity, with results summarized in Fig. 2. Distinct differences were evident between footwear (SFW) and apparel (AS) suedes, consistent with their functional requirements. Footwear groups (SFW1–3) exhibited higher thermal conductivity values (0.0556 – 0.0576 W/m·K) compared with apparel samples (0.0527 – 0.0530 W/m·K).

The variation in thermal conductivity among the suede samples can be explained by differences in their pore structure and density. Leather is a naturally porous material composed of collagen fibers, and the size and distribution of these pores directly affect heat transfer. Loosely structured leathers with wider and irregular pores contain more air gaps, which act as insulating barriers and therefore exhibit lower thermal conductivity. In contrast, denser and more compact leathers have smaller pores and increased fiber-to-fiber contact, allowing heat to pass more easily through the structure. Consequently, footwear suedes, which typically have tighter and thicker structures, show higher thermal conductivity compared to apparel suedes, which maintain lower conductivity and improved insulation due to their more open and porous morphology. Higher conductivity enhances heat dissipation but can also produce a cooler feel on first contact, consistent with their use in shoes requiring durable and stable microclimates. These findings are in line with reports showing that leather type and thickness directly influence heat flow across the leather structure [7, 8].

Resistance to heat flow was significantly greater in footwear samples (0.0210 – 0.0224 m^2K/W) compared to apparel groups (0.0152 – 0.0159 m^2K/W). This outcome is primarily governed by thickness differences, as footwear samples averaged 1.13 – 1.29 mm, whereas apparel samples were thinner (0.80 – 0.84 mm). Greater thickness increases the air gap fraction within the structure, thereby raising insulation capacity. These results are consistent with earlier studies showing that thickness is a dominant factor in determining the insulation of shoe uppers [31]. Such enhanced resistance is advantageous in footwear, where protection against environmental fluctuations is essential.

Footwear suedes showed a slight difference in the thermal absorptivity values, which were in the range of 229.2 – 259.5 $W\cdot s½\cdot m^{-2}\cdot K^{-1}$ compared with these values 239.5 – 246.1 $W\cdot s½\cdot m^{-2}\cdot K^{-1}$ for apparel suedes, suggesting that footwear materials impart a cooler tactile sensation upon first contact. This is attributable to moderate a higher conductivity and density, which accelerate transient heat transfer from the skin to the material. Conversely, apparel suedes exhibited slightly lower absorptivity, producing a warmer hand feel consistent with garment applications requiring tactile comfort. Previous research confirms that absorptivity is critical for immediate thermal sensation and directly linked to structural density and finishing [8, 32].

In summary, the obtained results show how thickness, density, and tanning processes differentiate thermal behaviour between footwear and apparel suedes. Footwear suedes emphasize insulation and structural durability, providing cooler tactile sensations suited for shoe uppers exposed to fluctuating climates and mechanical stresses. Apparel suedes, in contrast, favor softness, flexibility, and a warmer tactile perception, aligning with comfort expectations in garments. These results corroborate the broader view that thermal comfort is application-specific and must be optimized in tandem with air and vapour permeability to create balanced microclimates [1, 3, 29].

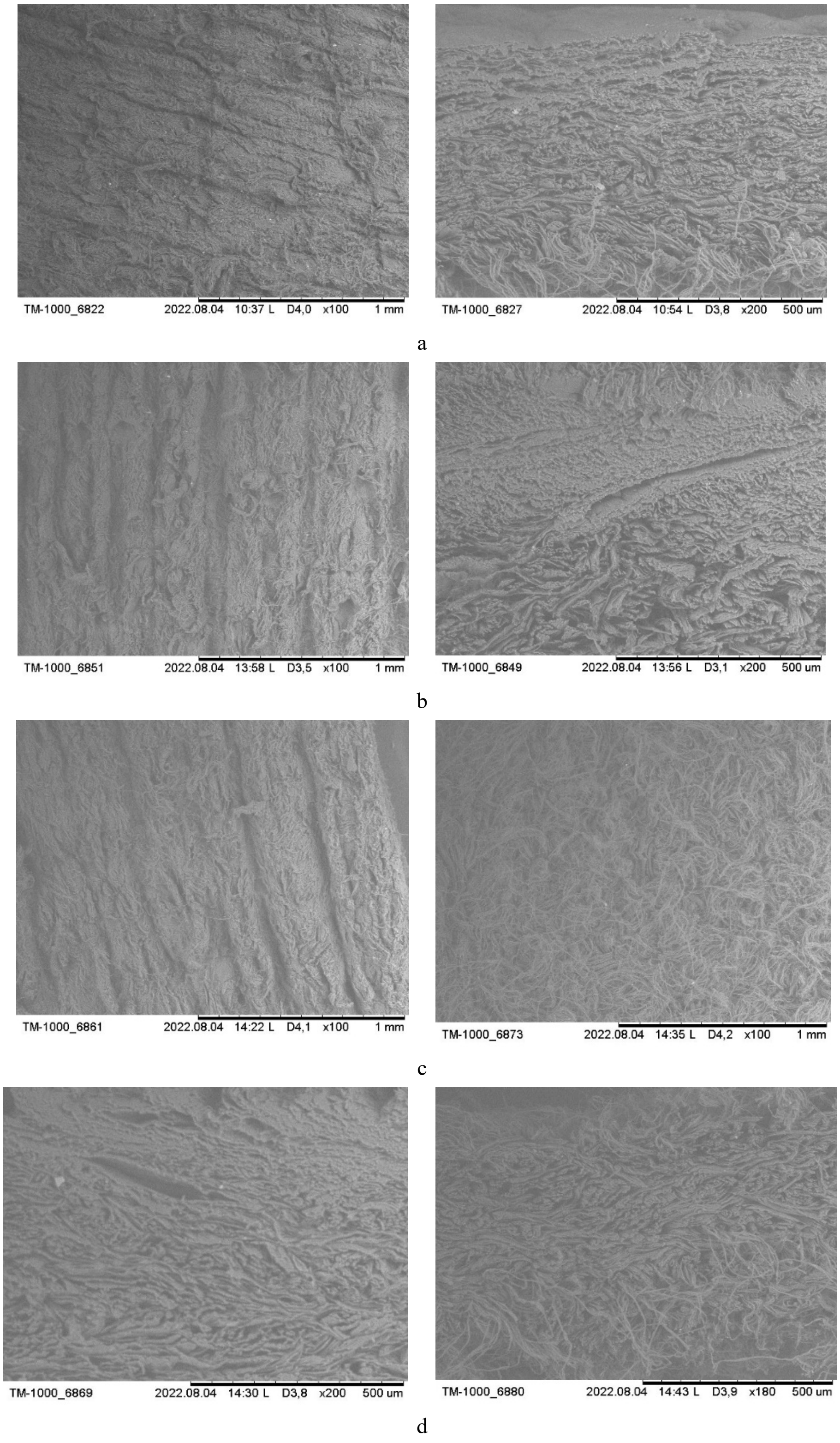


a b c

Fig. 2. Suede leathers for footwear (SFW) and apparel (AS): a – thermal conductivity; b – resistance; c – absorptivity

3.4. Morphological characteristics of the suede leathers

The SEM images of the suede side and the cross-sections of the leather samples for footwear and apparel are shown in Fig. 3. The characteristic appearance of the analyzed leathers differed depending on the treatment and the purpose of usage. While the surface of footwear leathers exhibits a rougher appearance (Fig. 3 a1 – c1), garment leathers possess a more uniform and smoother structure (Fig. 3 d1, e1). The unique surface morphology of suede leathers, as clearly shown in the SEM micrographs in Fig. 3, offers a structural explanation for the differences observed in their thermal comfort characteristics. Footwear suedes (Fig. 3 a – c) exhibit a coarser, denser, and more compact fibrous network with narrower pores.



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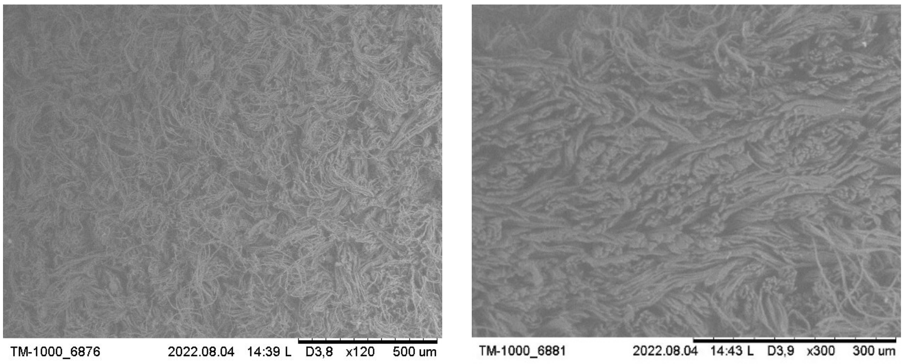

e

Fig. 3. Scanning electron micrographs of suede leather samples: a, b, c – for footwear; d, e – for apparel; surface images on the left (1) and cross-sections on the right (2)

This structure, visible in the images, promotes greater fiber-to-fiber contact, which results in higher thermal conductivity for effective heat dissipation and a higher thermal absorptivity, explaining the cooler initial feel upon contact. In contrast, the apparel suedes (Fig. 3 d, e) display a more homogeneous, open, and porous morphology. The larger and more irregular air gaps evident in these micrographs act as efficient insulating barriers, leading to the measured lower thermal conductivity for superior body heat retention and a lower thermal absorptivity that produces a warmer initial tactile sensation. Consequently, the SEM analysis confirms that the tailored pore architecture directly dictates the thermal performance: the dense matrix of footwear suedes manages heat transfer for footwear microclimate stability, while the open, porous structure of apparel suedes prioritizes insulation and immediate warmth for garment comfort.

4. CONCLUSIONS

This study systematically compared the thermo-physiological comfort properties of suede leather for footwear and apparel, addressing a critical research gap. Chromium-tanned apparel suedes demonstrated superior tensile strength, elongation, and permeability, making them highly suitable for garments requiring flexibility, breathability, and wearer comfort. Wet-white tanned footwear suedes exhibited higher thermal resistance and absorptivity, providing insulation and a cooler tactile sensation essential for maintaining a stable foot microclimate. Tear strength results confirmed adequate durability in both categories, with footwear samples showing variability linked to processing factors such as splitting and finishing. These findings reveal that the thermal properties of suede materials make them suitable for their intended application areas. These insights not only advance the understanding of leather thermo-physiology but also support innovation in comfort-driven product design in line with evolving consumer expectations.

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