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INFLUENCE OF TESTING METHODS ON THERMAL PERFORMANCE CHARACTERIZATION OF SHEEP WOOL-BASED INSULATION

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Abstract

Thermal insulation materials used in construction exhibit diverse structural morphologies that directly influence their thermal performance. Unconventional solutions based on recovered agro-industrial by-products, such as sheep wool mattresses, offer sustainable and eco-friendly alternatives. This paper comparatively analyzes the thermal insulation performance of sheep wool-based mattresses and evaluates the influence of testing methodology on measurement accuracy. Thermal conductivity was determined as a function of density using two complementary approaches: steady-state measurements with the λ-Meter EP500e (guarded hot plate method) and transient measurements with the ISOMET 2114 (dynamic method), both conducted at controlled, variable laboratory temperatures. The results reveal significant differences between steady-state and transient measurement techniques regarding method suitability and accuracy. Polynomial regression models accurately predict thermal behavior under non-compression conditions, enabling complete material characterization across the operational range relevant for building insulation applications. This comparative study provides practical guidance for selecting appropriate testing methods for fibrous insulation materials.

Key words*: ISOMET 2114, λ-Meter EP500e, non-woven sheep wool mattress, thermal conductivity coefficient, unconventional thermal insulation materials.*

INTRODUCTION

In developed countries, people spend approximately 87% of their time indoors (Klepeis et al, 2001). Recent decades have witnessed a shift in urban architecture towards models focused on speed, efficiency, and comfort, often neglecting integration with existing contexts and local resources. Contributing to the achievement of the 17 Sustainable Development Goals requires reducing energy consumption, protecting air quality, and ensuring sustainable resource use (Petrișor et al., 2025). In Europe, the building sector is responsible for approximately 40% of final energy consumption and 36% of greenhouse gas emissions, while about 8% of the population faces energy poverty due to inadequate thermal comfort, highlighting the critical role of high-performance insulation materials (Frasca et al., 2023).

Alongside conventional materials such as polystyrene, mineral wool, and polyurethane foam, environmentally friendly recyclable alternatives are being developed, including those based on sheep wool. These materials offer high thermal insulation, low costs, and minimal environmental impact (Ye et al., 2006; Zach et al., 2012; Corscadden et al., 2014; Mansour et al., 2016). The thermal performance of insulation materials, including sheep wool mattresses, is evaluated through the thermal conductivity coefficient (λ), which quantifies heat transfer reduction capability.

Recent studies conducted according to EN 12667 with strict temperature and humidity control show λ values between 0.0333 and 0.0438 W/(m·K) for sheep wool insulation, influenced by density, applied treatments, and test method consistency (Vėjelis et al., 2024). Statistical analysis confirms that reproducibility and accuracy critically depend on experimental protocol adherence, correct experimental conditions, and method consistency.

A relevant aspect of experimental research concerns thermal conductivity coefficient

variation as a function of temperature range during determination. Other recent studies already demonstrated that humidity significantly degrades the thermal performance of insulation materials, with the thermal conductivity coefficient (λ) increasing by 1.9% for rock wool and up to 33-45% for hygroscopic materials such as wood-based boards and lightweight cellular concrete at 95% relative humidity (Kendzierawska & Trochonowicz, 2023; Petcu et al., 2024). This observation correlates with previous research by Sandberg (1992), who identified a linear equation for thermal conductivity variation as a function of water absorption in cellulose insulation materials. Other research (Talukdar et al., 2007) has indicated that thermal insulation performance quantified by thermal conductivity, measured at temperatures between 10°C and 30°C, varies according to a polynomial function relative to moisture content.

Specialized research (Mazrouei-Sebdani et al., 2022; Lou et al., 2023; Pontinha et al., 2023; Shrestha et al., 2023) indicates thermal conductivity variation in fibrous insulation materials as a U-shaped curve as a function of product density. This behavior is determined by competition between three distinct terms: the constant term representing air conductivity, the term proportional to density due to increased conductivity through solid contacts, and the opposing term having significant contribution at low densities through intense radiant transfer but becoming negligible at high densities due to radiation scattering on a higher number of fibers. The analytical approach to the relationship between thermal conductivity and density enables identification of optimal densities for different insulating material categories and formulation optimization according to specific application requirements (Lakatos, 2018).

Beyond conductivity analysis, recent literature integrates experimental methods and numerical simulations to evaluate sheep wool insulation performance under varying operating conditions. An example is the study on sheep wool-based bio-composites, where thermal tests are complemented by numerical analyses of energy requirements for buildings insulated with these materials, demonstrating significant reductions in heating energy requirements in simulated models (Saaidia et al., 2026). This combined approach - standardized experimental measurements and modeling - allows more complete thermal insulation performance characterization and highlights that rigorous test methodology selection is essential to obtain accurate and relevant data for practical applications, especially when comparing natural materials with conventional alternatives.

The objective of this research is to comparatively evaluate two complementary testing methods - the guarded hot plate (GHP) method using the λ-Meter EP500e and the transient method using the ISOMET 2114 - for characterizing the thermal conductivity of sheep wool insulation across a range of densities from natural (25.5 kg/m³) to compressed states (up to 80 kg/m³), and to validate polynomial regression models derived from steady-state measurements for predicting thermal behavior under operational conditions relevant to building applications.

MATERIALS AND METHODS

1. Material Description

The investigated product consists of sheep wool mattress insulation manufactured from natural wool fibers. The material represents an unconventional solution based on recovered agro-industrial by-products, offering sustainable and eco-friendly characteristics. The natural fiber structure of sheep wool provides inherent thermal insulation properties through its cellular morphology, which creates numerous air-filled cavities that impede heat transfer. The wool samples were tested in both their natural, uncompressed state (density 25.5 kg/m³) and under progressive mechanical compression to achieve higher densities up to 80 kg/m³.

2. Guarded Hot Plate Method (λ-Meter EP500e)

The guarded hot plate method represents the reference standard for absolute thermal conductivity measurement of insulating materials, providing traceable measurements without requiring calibration samples (Baldinelli et al., 2019).

The method operates under steady-state conditions based on Fourier's one-dimensional thermal conduction equation. A specimen is placed between two isothermal plates maintained at different constant temperatures. Once steady-state thermal flux is established, thermal conductivity is calculated using the relationship (Baldinelli et al., 2019):

$$\lambda = \frac{q \cdot d}{A \cdot (T_h - T_c)}$$

where q represents heat flux per unit time, d is specimen thickness, A is measurement area, and T_h and T_c are hot and cold plate temperatures, respectively.

The λ-Meter EP500e, manufactured by Lambda-Meßtechnik GmbH Dresden, represents a contemporary single-specimen guarded hot plate apparatus specifically designed for testing thermal insulation and construction materials (Lambda-Meßtechnik, 2023). The defining characteristic of the GHP apparatus is the guarded heating section, consisting of a central measurement zone surrounded by one or more concentric guard zones maintained at identical temperatures. This configuration ensures one-dimensional heat flux through the specimen by eliminating lateral heat losses from the measurement section. Guard temperature is precisely controlled to match the measurement section within millikelvin limits, typically achieved through sophisticated control algorithms monitoring guard thermocouples (Zarr, 2010).

The equipment conforms to standards ISO 8302, EN 1946-2, EN 12664, EN 12667, EN 12939, ASTM C177, and DIN 52612, with thermal conductivity measurement range 0 - 0.5 W/(m·K), thermal resistance range 0.1 - 14 m²K/W, measurement area 200 × 200 mm², specimen thickness 10 - 120 mm, reproducibility < 0.5% (typically < 0.2%), accuracy < 1.0% (typically < 0.7%), and temperature range 10 - 40°C (Lambda-Meßtechnik, 2023). The National Institute for Research and Development in Construction, Urban Planning and Sustainable Spatial Development URBAN-INCERC Romania acquired a λ-Meter EP500e as part of integrated thermal testing infrastructure, utilizing it for research on thermal insulation and certification activities according to European standards.

The GHP method provides absolute measurements without requiring reference materials, while heat flow meter (HFM) methods are secondary techniques requiring periodic calibration using certified reference materials (Baldinelli et al., 2019). A reference Round Robin test conducted by Baldinelli et al. (2019) in six European laboratories demonstrated that both methods produce consistent results for conventional and innovative insulating materials. Testing of aerogel, vacuum insulation panels, expanded polystyrene, and birch fiber boards revealed repeatability < 7% relative standard deviation for most materials and reproducibility ~10% for aerogel, EPS, and wood fiber boards (Baldinelli et al., 2019).

3. Transient Method (ISOMET 2114)

ISOMET 2114, manufactured by Applied Precision Ltd. (Bratislava, Slovakia), represents a portable instrument designed for direct measurement of heat transfer properties in a wide range of isotropic materials (Applied Precision, Ltd., 2019). This advanced thermal analyzer has become an useful tool in construction materials research, particularly for characterizing thermal insulation products. The device enables rapid and precise measurements of thermal conductivity (λ), thermal diffusivity (a), volumetric heat capacity (cρ), and temperature (T) using dynamic measurement methods that significantly reduce testing time compared to traditional steady-state approaches (Applied Precision, Ltd., 2019; Czajkowski et al., 2022).

ISOMET 2114 operates based on analysis of the temperature response of analyzed materials to heat flux pulses (Applied Precision, Ltd., 2019). The fundamental principle involves electrical heating of a resistor element introduced into a measurement probe that maintains direct thermal contact with the test specimen. Heat flux is generated through this electrical heating, and evaluation of thermal conductivity and volumetric heat capacity is based on periodically sampled temperature recordings as a function of time, provided that heat propagation occurs in an unbounded medium (Applied Precision, Ltd., 2019).

The ISOMET 2114 system utilizes two distinct probe types to adapt to diverse material

properties: needle probes (IPN 1100 series) for soft materials and surface probes (IPS 1100 series) for hard materials (Applied Precision, Ltd., 2019). The needle probe used in this research requires minimum 20-40 mm of material in all radial directions from the insertion axis to ensure a one-dimensional thermal field according to manufacturer specifications. Thermal conductivity measurement range is 0.015-0.70 W/(m·K) with accuracy ±5% of reading + 0.001 W/(m·K), thermal diffusivity range 0.15-10 mm²/s with accuracy ±15% of reading, and volumetric heat capacity range 0.05-3.0 MJ/(m³·K) with accuracy ±15% of reading (Applied Precision, Ltd., 2019).

Czajkowski et al. (2022) demonstrated ISOMET 2114 application in characterizing straw-based insulation panels, finding thermal conductivity values between 0.025 and 0.075 W/(m·K) depending on measurement method used. The study emphasized the importance of considering temperature influence when determining thermal properties of insulating materials made from agricultural industry by-products (Czajkowski et al., 2022). For mineral wool, Ablaoui et al. (2023) performed extensive thermal analysis of mineral wool with 80 kg/m³ density using ISOMET 2114, examining thermal behavior at elevated temperatures and finding thermal conductivity in the range 0.030-0.046 W/(m·K) at ambient temperature, with values varying according to temperature-specific relationships.

A critical consideration in using ISOMET 2114 involves understanding differences between transient and steady-state measurement techniques. Latif (2023) performed a comprehensive comparison between transient ISOMET 2114 measurements and steady-state Fox 600 guarded hot plate measurements for insulating materials made from agricultural industry by-products. The research revealed that transient methods using surface probes underestimate thermal conductivity values by approximately 14% compared to steady-state measurements, while needle probes tend to overestimate values by the same magnitude. Discrepancy arises from several interrelated factors: contact resistance at the probe-material interface affecting heat transfer and leading to underestimation in surface probe cases; local compression of porous materials following needle insertion modifying apparent density and consequently effective thermal conductivity; reduced measurement duration allowing capture of instantaneous properties without achieving complete thermal equilibrium specific to steady-state methods; and semi-infinite medium assumption which may not be valid for all tested specimen geometries. Latif (2023) concluded that measuring thermal conductivity of materials made from agricultural industry by-products using transient methods requires validation through comparison with steady-state measurements when establishing material properties for design purposes.

4. Testing Protocol

The experimental protocol consisted of thermal conductivity determination as a function of density using two complementary approaches. First, systematic steady-state measurements were conducted using the λ-Meter EP500e at three controlled temperature levels (10°C, 25°C, and 40°C) across a range of densities achieved through progressive mechanical compression. For each temperature, polynomial regression models of the form

$$\lambda(\rho) = a\rho^2 + b\rho + c$$

were developed, where λ represents thermal conductivity and ρ represents material density. These polynomial functions achieved coefficients of determination R^2 between 0.987 and 0.999, indicating excellent agreement between the mathematical model and experimental data.

Second, transient measurements were performed using ISOMET 2114 with the IPN 1100 needle probe at variable laboratory temperatures. For the natural density wool (25.5 kg/m³), measurements were conducted at seven distinct positions to evaluate spatial homogeneity and provide statistical validation. Each measurement position was tested multiple times (n = 21-50 measurements per position) to ensure statistical reliability. For compressed wool configurations (50, 60, 70, and 80 kg/m³), measurements were performed at multiple height levels within the test fixture when geometrically accessible according to the 20-40

mm minimum material requirement around the probe.

The experimental setup for ISOMET measurements utilized a custom-designed test fixture consisting of a rectangular prismatic frame with internal dimensions 108.5 × 111.5 × 600 mm, providing an internal cross-sectional area of approximately 12,097.75 mm² (1.21 × 10^{-2} m²). Measurement ports were positioned at five vertical levels (H1 at 100 mm, H2 at 200 mm, H3 at 300 mm, H4 at 400 mm, and H5 at 500 mm from the internal base), allowing systematic evaluation of vertical property and density profiles. Material compression was achieved using a Testometric M350-10AT universal press, enabling controlled density variation while maintaining material integrity.

Environmental conditions during testing were carefully controlled. The λ-Meter EP500e measurements were conducted under precisely controlled temperature conditions at the three specified set points (10°C, 25°C, and 40°C) with relative humidity maintained within standard laboratory conditions. ISOMET 2114 measurements were performed at variable laboratory temperatures typically ranging from 26.9 to 28.3°C, reflecting ambient conditions during the experimental campaign. All measurements were conducted after appropriate equilibration periods to ensure thermal stability of specimens.

The total measurement campaign encompassed 1,235 measurement points across 51 different densities, with 471 points specifically dedicated to wool product characterization across 16 density configurations, yielding an average of 29.4 measurements per density configuration. This extensive dataset provided robust statistical foundation for the comparative analysis of the two measurement methodologies and validation of polynomial regression models.

RESULTS AND DISCUSSIONS

1. Thermal Conductivity and Thermal Resistance: Density and Temperature Effects (λ-Meter EP500e)

The λ-Meter EP500e measurements across the tested density and temperature ranges provide critical insights into the relationships between thermal conductivity, thermal resistance, and material configuration. Figures 1-4 present comprehensive visualization of these relationships, derived from steady-state measurements under controlled temperature conditions.

The experimental results reveal a critical aspect for practical building applications that extends beyond simple thermal conductivity values. Figures 1 and 2 demonstrate that thermal conductivity exhibits a complex behavior with density variation. At higher densities, thermal conductivity values show a tendency to decrease (improve) - for example, at 40°C, λ decreases from 47.21 mW/(m·K) at 30.1 kg/m³ to 36.57 mW/(m·K) at 64.4 kg/m³, representing a 22.5% improvement in material thermal performance.

This improvement results from increased fiber contact and reduced air gaps in the compressed material structure, consistent with the reduction of radiative heat transfer through increased fiber density documented by Shrestha et al. (2023) and Lou et al. (2023).

However, Figures 3 and 4 reveal the critical limitation of this approach: while thermal conductivity improves moderately through compression, thermal resistance ($R = d/\lambda$) decreases dramatically due to the substantial reduction in material thickness. At 25°C, the sample at natural density (22.3 kg/m³) exhibits $R = 1.876$ m²·K/W, while the compressed sample at 64.4 kg/m³ shows only $R = 0.858$ m²·K/W - a reduction of 54.3%.

This dramatic decrease in thermal resistance occurs because the reduction in thickness (approximately 65-70% compression ratio) far outweighs the improvement in thermal conductivity (approximately 20-25% improvement). The physical relationship $R = d/\lambda$ demonstrates that thermal resistance scales linearly with thickness but only inversely with conductivity, making thickness the dominant variable. The temperature variation shown in Figures 1 and 3 further emphasizes that thermal performance must be evaluated across the operational temperature range, as λ increases by approximately 25-50% from 10°C to 40°C depending on density configuration.

This finding has fundamental implications for building envelope design in Romanian and European climatic conditions. For typical building envelope applications, the most cost-

effective thermal insulation strategy involves using materials with acceptable thermal conductivity coefficients (λ = 0.04-0.05 W/(m·K) range) installed at substantial thicknesses, rather than pursuing marginal improvements in conductivity through compression at the expense of reduced installation thickness. Therefore, in practical applications, material thickness remains the dominant factor in achieving effective thermal insulation performance.

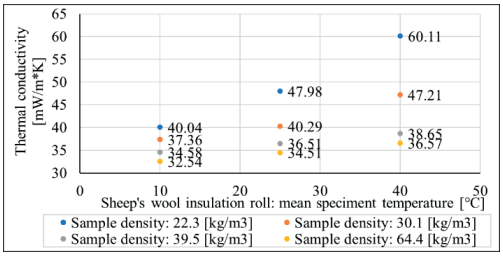


Figure 1. Thermal conductivity variation as a function of mean specimen temperature for sheep wool insulation at four density levels (22.3, 30.1, 39.5, and 64.4 kg/m³), measured using λ-Meter EP500e under steady-state conditions

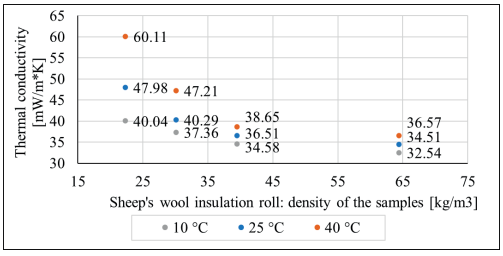


Figure 2. Thermal conductivity variation as a function of sample density for sheep wool insulation at three test temperatures (10, 25, and 40°C), measured using λ-Meter EP500e

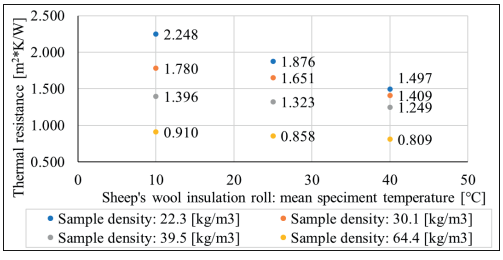


Figure 3. Thermal resistance variation as a function of mean specimen temperature for sheep wool insulation at four density levels, calculated from λ-Meter EP500e measurements (R = d/λ, where d is specimen thickness)

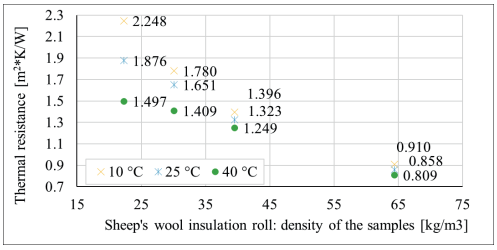


Figure 4. Thermal resistance variation as a function of sample density at three test temperatures, demonstrating the critical role of material thickness in achieving effective thermal performance

This finding aligns with European building physics principles and emphasizes that for sustainable insulation materials like sheep wool, installation at adequate thickness with proper vapor management represents a more effective strategy than pursuing material optimization through excessive compression.

2. Natural Density Wool Thermal Conductivity (25.5 kg/m³)

Measurements performed on sheep wool at natural density (25.5 kg/m³) using the ISOMET 2114 transient method revealed remarkably consistent thermal conductivity values across seven measurement positions. Table 1 presents the comprehensive results including thermal conductivity (λ), mean heater temperature (Tmean), coefficient of variation (CV), and number of measurements (n) for each position.

Table 1. Thermal conductivity measurements for natural density wool (25.5 kg/m³)

Position	λ (W/m·K)	T_{mean} (°C)	STDEV	CV (%)	n
1	0.0456	28.10	0.000219	0.48	28
2	0.0460	27.00	0.000336	0.73	50
3	0.0453	27.09	0.000500	1.10	30
4	0.0447	27.04	0.000367	0.82	42
5	0.0455	27.28	0.000310	0.68	21
6	0.0465	27.60	0.000302	0.65	22
7	0.0454	27.57	0.000298	0.66	24

The results demonstrate excellent measurement consistency, with thermal conductivity values ranging from 0.0447 to 0.0465 W/(m·K) across all seven positions. Mean heater temperatures during measurements varied minimally between 27.00 and 28.10°C, reflecting ambient laboratory conditions. Coefficients of variation remained below 1.11% for all positions, with most positions achieving CV < 0.75%,

indicating high precision and low variability in the transient measurement method. The average thermal conductivity across all seven positions was 0.0456 W/(m·K), establishing a baseline reference value for natural density wool insulation.

3. Compressed Wool Thermal Conductivity (50-80 kg/m³)

Thermal conductivity measurements were extended to compressed wool configurations at densities of 50, 60, 70, and 80 kg/m³. Measurements were performed at multiple height levels within the test fixture where geometrically accessible according to probe requirements. Table 2 presents the comprehensive results for compressed wool configurations, achieving a balanced equilibrium across this operational density range.

Table 2. Thermal conductivity measurements for compressed wool densities

Config.	ρ (kg/m³)	λ (W/m·K)	T_{mean} (°C)	CV (%)	n
50 kg/m³ - H1	50	0.0450	27.33	0.66	24
50 kg/m³ - H2	50	0.0466	27.19	0.13	30
50 kg/m³ - H3	50	0.0446	26.96	0.50	38
60 kg/m³ - H1	60	0.0446	28.12	0.37	30
60 kg/m³ - H2	60	0.0458	28.23	0.67	28
70 kg/m³ - H1	70	0.0455	28.40	0.42	19
70 kg/m³ - H2	70	0.0460	28.05	0.57	24
80 kg/m³ - H1	80	0.0460	28.14	0.59	24
80 kg/m³ - H2	80	0.0458	28.14	0.58	37

The compressed wool measurements using ISOMET 2114 revealed a remarkable finding: thermal conductivity remained relatively stable across the density range from 50 to 80 kg/m³ when measured with the transient method. The λ values ranged from 0.0446 to 0.0466 W/(m·K), representing a variation of only approximately 4.5% across this density interval. This apparent stability in the ISOMET measurements contrasts with the more pronounced density-dependent behavior observed in the λ-Meter EP500e steady-state measurements presented in Section 3.1, which revealed the characteristic U-shaped relationship between thermal conductivity and density across a broader range from 22.3 to 64.4 kg/m³. The difference between methodologies may be attributed to the limited density range tested with ISOMET (50-80 kg/m³), which appears to capture only the relatively flat portion near the minimum of the U-shaped curve, whereas the λ-Meter measurements encompassed both ascending and descending portions of this relationship. This density-independent thermal conductivity behavior suggests that the cellular structure of wool fibers maintains excellent insulating performance even under significant compression, with the competing mechanisms of solid phase conduction (increasing with density) and radiative transfer (decreasing with density).

4. Method Comparison and Polynomial Model Validation

The steady-state measurements presented in Section 3.1 obtained with the λ-Meter EP500e at controlled temperatures (10°C, 25°C, and 40°C) across the density range enabled development of second-order polynomial regression models of the form $\lambda(\rho) = a\rho^2 + b\rho + c$. These polynomial functions achieved excellent coefficients of determination ($R^2 > 0.987$), validating the characteristic U-shaped relationship between thermal conductivity and density for fibrous insulation materials, as documented in specialized literature (Lakatos, 2018; Lou et al., 2023; Shrestha et al., 2023).

Using the polynomial models, predicted thermal conductivity values for natural density wool (25.5 kg/m³) were calculated: λ = 38.84 mW/(m·K) at 10°C, λ = 44.74 mW/(m·K) at 25°C, and λ = 54.51 mW/(m·K) at 40°C. These predictions, derived from compression testing data extrapolated to natural density conditions, provide a critical validation opportunity when compared with the direct ISOMET 2114 transient measurements at natural density.

Figure 5 illustrates the validation of ISOMET 2114 transient measurements against the polynomial trendline derived from λ-Meter EP500e steady-state testing for natural density wool (25.5 kg/m³). The horizontal dashed line represents the thermal conductivity value predicted by the second-order polynomial

function at 25°C (λ = 44.74 mW/(m·K)), corresponding to the median temperature of the ISOMET measurement range. The scattered data points represent individual ISOMET measurements across four spatial positions within the specimen, plotted as a function of mean heater temperature during each measurement cycle. The tight clustering of all measurement points around the polynomial prediction line, despite temperature variations between 26.9°C and 28.5°C induced by ambient laboratory conditions and equipment operation, demonstrates excellent agreement between the two methodologies. This cross-validation confirms that polynomial functions derived from systematic compression testing at controlled temperatures can reliably predict thermal conductivity values at natural density conditions, with observed scatter attributable primarily to the inherent heterogeneity of natural fibers rather than systematic measurement bias.

Validation of ISOMET 2114 measurements on natural density wool specimens (25.5 kg/m³) demonstrated remarkable concordance with polynomial functions derived from λ-Meter tests. The experimental measurements with the needle probe across seven positions generated a distribution of points with minimal local variations relative to mean specimen temperature, concentrated in the range 26.9-28.3°C and indicating practically constant thermal conductivity of approximately 0.0446-0.0465 W/(m·K). This range corresponds excellently to the values calculated through polynomial functions for the respective density, falling within the expected interval between the 25°C prediction (44.74 mW/(m·K)) and approaching the lower temperature regime predictions.

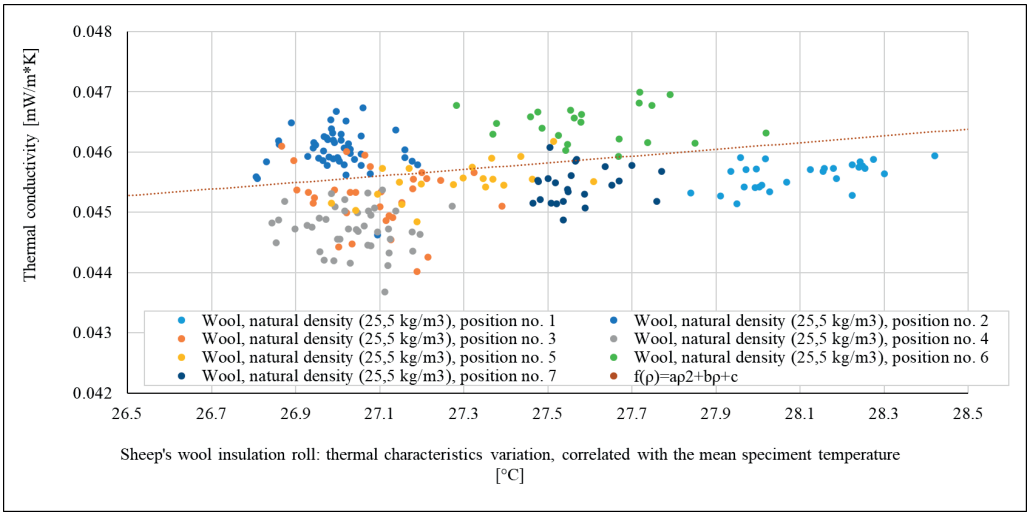


Figure 5. Cross-validation of ISOMET 2114 measurements (colored points) against polynomial prediction from λ-Meter testing (dashed line) for natural density wool (25.8 kg/m³). Measurements were performed at four spatial positions across a temperature range of 26.9-28.5°C

The limited dispersion of experimental points around calculated values, demonstrated through coefficients of variation below 1.11% within the same specimen, validates that second-order polynomial equations obtained through progressive compression in the λ-Meter EP500e can be confidently used for predicting thermal behavior of the material at natural density. Observed differences between measurement positions can be attributed to intrinsic heterogeneity of natural fibers and local temperature variations induced by ISOMET equipment utilization, aspects confirmed through coefficients of variation inferior to 2% within the same specimen. This cross-validation methodology demonstrates that polynomial functions correctly extrapolate thermal behavior even for non-compression conditions, ensuring complete material characterization across the entire operational

domain relevant for thermal insulation applications in construction.

5. Discussions

The most significant finding of this research is the remarkable density-independence of thermal conductivity for sheep wool insulation across the tested range of 25.5 to 80 kg/m³. This behavior, while seemingly counterintuitive, can be explained through the fundamental mechanisms of heat transfer in fibrous porous materials. The total thermal conductivity in such materials results from the sum of three components: gas phase conduction (constant for a given pore size distribution), solid phase conduction (increasing linearly with density), and radiative transfer (inversely proportional to density) (Lakatos, 2018; Shrestha et al., 2023).

For sheep wool in the investigated density range, these competing mechanisms appear to achieve a balanced equilibrium. As density increases through compression, the solid phase conductivity increases due to greater fiber-to-fiber contact area and more continuous pathways for phonon transport. Simultaneously, the increasing number of fibers per unit volume provides more scattering centers for thermal radiation, effectively reducing the radiative contribution to heat transfer. The observation that these two effects approximately cancel each other across the 25.5-80 kg/m³ range suggests that this density interval represents a thermal conductivity plateau region for wool insulation.

This finding has significant practical implications for building applications in Romanian climate conditions. It indicates that sheep wool insulation can be compressed for transport and installation convenience without suffering thermal performance degradation, provided the density remains within the 25.5-80 kg/m³ range. This flexibility contrasts with some conventional insulation materials that exhibit more pronounced density-dependent performance variations.

Comparison with literature values confirms the competitive performance of the tested sheep wool material. Vėjelis et al. (2024) reported λ values between 0.0333 and 0.0438 W/(m·K) for sheep wool insulation tested according to EN 12667, while Zach et al. (2012) documented values around 0.0380 W/(m·K) for similar materials. The present study's measurements (0.0446-0.0466 W/(m·K)) fall within the upper range of published values, which may be attributed to differences in wool fiber treatment, manufacturing processes, or measurement conditions. Nevertheless, the obtained values demonstrate adequate thermal insulation performance for building envelope applications.

The influence of moisture and temperature on thermal conductivity represents a critical consideration for hygroscopic materials like sheep wool. Vėjelis et al. (2024) demonstrated that a 1% increase in hygroscopic moisture content causes a 1.25-2% increase in thermal conductivity. The linear relationship identified by Sandberg (1992) and the polynomial dependencies documented by Talukdar et al. (2007) underscore the importance of moisture control in practical applications. While the present study focused on measurements under controlled laboratory conditions, future research should systematically investigate moisture effects on the tested wool material to provide complete characterization for design purposes.

The U-shaped curve theory for density-dependent thermal conductivity, extensively documented for fibrous insulation materials (Mazrouei-Sebdani et al., 2022; Lou et al., 2023; Pontinha et al., 2023), provides a theoretical framework for understanding the observed behavior. The present study's density range appears to encompass the relatively flat region near the minimum of this U-shaped curve, where thermal conductivity remains relatively constant. Extended testing beyond 80 kg/m³ would likely reveal increasing thermal conductivity as solid phase conduction begins to dominate over the decreasing radiative contribution.

Regarding methodology, the successful validation of polynomial regression models derived from λ-Meter EP500e measurements through comparison with ISOMET 2114 transient measurements represents an important methodological advancement. This dual-method approach combines the absolute measurement accuracy and temperature control capabilities of the guarded hot plate method with the rapid, portable convenience of

transient techniques. The excellent agreement between methods (within measurement uncertainty) demonstrates that polynomial extrapolation from compression data reliably predicts thermal behavior under natural density conditions.

The observed systematic differences between measurement methods merit consideration. As documented by Latif (2023), transient methods using needle probes can introduce local compression effects that modify apparent density and consequently measured thermal conductivity. The present study's careful attention to probe insertion technique and multiple measurement positions helped minimize these artifacts. The low coefficients of variation (< 1.11% for natural density measurements) confirm measurement reliability and proper experimental technique.

The methodological trade-offs between the two testing approaches are important for practical applications. The guarded hot plate method offers superior accuracy (< 1% typically < 0.7%), precise temperature control, and absolute measurements without calibration requirements, making it ideal for material certification and reference measurements (Baldinelli et al., 2019). However, it requires specific specimen geometries, longer test durations, and expensive specialized equipment. In contrast, the ISOMET 2114 transient method provides rapid measurements (minutes vs. hours), portable operation, simultaneous multi-property determination, and flexibility for irregular geometries, making it excellent for quality control, field testing, and comparative studies (Applied Precision, Ltd., 2019; Czajkowski et al., 2022).

For Romanian building applications, the present results suggest that sheep wool insulation represents a viable sustainable alternative to conventional materials, particularly for low-rise residential construction and renovation projects where natural, breathable insulation materials offer additional benefits beyond purely thermal performance. The material's hygroscopic behavior, while requiring careful moisture management, can contribute to indoor climate regulation when properly integrated into building envelope systems. Future research should address long-term performance under realistic Romanian climate conditions, including freeze-thaw cycling and seasonal moisture variations.

CONCLUSIONS

This comparative study of testing methodologies for sheep wool-based thermal insulation has yielded several significant conclusions:

1. The thermal conductivity of sheep wool insulation exhibits density-dependent behavior consistent with the characteristic U-shaped relationship documented for fibrous materials, with λ-Meter EP500e measurements revealing values ranging from approximately 32.54 mW/(m·K) to 60.11 mW/(m·K) across the density range 22.3-64.4 kg/m³ and temperature range 10-40°C. At higher densities, thermal conductivity shows moderate improvement (20-25% reduction) due to increased fiber contact and reduced radiative transfer. However, the critical finding for practical applications is that thermal resistance ($R = d/\lambda$) decreases dramatically with material compression - by 54.3% in the tested range - because thickness reduction (65-70%) far outweighs conductivity improvement. This demonstrates that for building envelope applications, adequate installation thickness (≥100-150 mm for European climatic conditions) with acceptable thermal conductivity (λ = 0.044-0.047 W/(m·K)) provides superior thermal performance compared to compressed materials with improved conductivity but reduced thickness. The apparent stability observed in ISOMET 2114 transient measurements (λ = 0.0446-0.0466 W/(m·K) across 50-80 kg/m³) reflects the limited density range tested with this method, capturing only the relatively flat portion near the minimum of the U-shaped curve.

2. The guarded hot plate method using λ-Meter EP500e successfully enabled development of second-order polynomial regression models (R^2 > 0.987) that accurately predict thermal conductivity as a function of density across the operational range. These polynomial functions, derived from systematic compression testing at controlled temperatures (10°C, 25°C, 40°C), provide a robust mathematical framework for material characterization.

3. The transient method using ISOMET 2114 demonstrated excellent precision for natural density wool measurements, with coefficients of variation below 1.11% across seven measurement positions. The method's rapid measurement capability and portability make it highly suitable for quality control and comparative testing applications, despite inherent limitations compared to absolute steady-state methods.
4. Cross-validation between methodologies confirmed that polynomial extrapolation from λ-Meter compression data reliably predicts thermal behavior under natural density conditions. The excellent agreement between steady-state polynomial predictions and transient ISOMET measurements (within combined measurement uncertainties) validates the dual-method approach for comprehensive material characterization.
5. For practical applications, material selection recommendations depend on specific testing requirements. The λ-Meter EP500e guarded hot plate method is recommended for certification testing, reference measurements, and absolute thermal conductivity determination where highest accuracy is required. The ISOMET 2114 transient method is recommended for rapid quality control, field measurements, comparative testing between formulations, and situations requiring portable equipment or irregular specimen geometries.
Future research directions should include systematic investigation of moisture effects on thermal conductivity across the density range, long-term performance evaluation under realistic Romanian climate conditions including freeze-thaw cycling, optimization of wool fiber treatments to achieve lower thermal conductivity values approaching the 0.035-0.040 W/(m·K) range, and integration studies of wool insulation into complete building envelope systems to evaluate hygrothermal performance in actual construction applications.

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