ADVANCING THERMAL INSULATION: AN INNOVATIVE STATISTICAL AND EXPERIMENTAL ANALYSIS OF POLYURETHANE-BASED MATERIALS

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ABSTRACT: This study integrated a framework combining construction industry–based questionnaire surveys with experimental thermal insulation performance evaluations. In contrast to previous polyurethane foam (PUF) insulation studies predominantly limited to laboratory-scale investigations or problem-based literature reviews, this approach directly connects field-based problem identification and material performance assessment. The selection of the right insulation materials requires careful consideration of property. PUF was identified as one of the most suitable materials in terms of physical, mechanical, and thermal properties; it is relatively simple to apply and cost-effective. The result reports that PUF insulation is through statistical and experimental methods. Statistical analyses were conducted on construction-related samples at a significance level of $\alpha = 0.05$; the regression model was $Y = 1.020 + 0.204X_1 + 0.289X_2 + 0.259X_3$. Tensile strength was 680 kPa, density was 97 kg/m^3, hardness was 70 Shore A, water absorption was 9%, decomposition temperature was 330°C, and thermal conductivity was 0.054 W/(m·K). The result indicates significant improvement in tensile strength and thermal performance; reductions in density and water absorption indicate the development of a lighter, more durable, and more effective thermal insulation system. These integrated improvements highlight the substantial advancement achieved in this study.

KEYWORDS: *Statistical; Polyurethane; Insulation; Thermal analysis.*

1.0 INTRODUCTION

Manufacturing processes and material selection for roofing insulation depend on insulation type, from material-specific production requirements and inherent physical, mechanical, and thermal characteristics. Roof insulation is widely recognized as an effective approach for reducing energy consumption and operational costs in both residential and industrial buildings. Effective insulation limits heat transfer, enhances acoustic performance, improves energy efficiency, and provides protection against moisture and fire hazards. However, insulation materials present advantages and limitations, requiring careful selection based on performance-related criteria [1,2]. Polyurethane Foam (PUF) is among the most widely used insulation materials because of its favorable thermal insulation performance, seamless application, lightweight structure, and water resistance [3]. Notwithstanding these benefits, conventional PUF exhibits limitations related to flammability and release of toxic gases during combustion.

Nevertheless, its application continues to increase the development of modified and eco-friendly PUF composite formulations [4]. Alternative insulation materials, including fiberglass, reflective aluminum foil, mineral wool, cellulose-based insulation, and calcium silicate, show variable fire resistance, moisture tolerance, durability, and thermal efficiency; however, each material also presents specific limitations that restrict widespread application [5]. As reported in the literature, PUF remains a preferred insulation material in roofing systems due to its balanced performance properties. Beyond insulation applications, the utilization of PUF has increased in adhesives, coatings, and structural materials in engineering systems [6]. On the other hand, the relatively limited thermal resistance and fire safety performance of conventional PUF necessitate further improvement. Previous literature reports that the incorporation of suitable fillers can enhance the thermal and structural performance of PUF-based composites [7]. In manufacturing engineering, key processing parameters, including foam density, cell morphology, injection speed, and mold temperature, must be carefully controlled to achieve consistent and reliable insulation quality. The requirement is reinforced by the rapid growth of the global polyurethane market price, which increased by approximately 39.25% between 2015 and 2022 and is projected to continue expanding through 2030. PUF-based products accounted for more than 65% of the total market share, driven largely by the increasing demand for energy-efficient construction solutions. PUF production involves chemical mixing that initiates polymerization, after which spray injection or compression molding processes occur [8].

Most studies on polyurethane foam (PUF) performance are limited to laboratory-scale evaluations, with insufficient consideration of on-site application challenges. In practice, insulation performance depends on intrinsic material properties along with extrinsic factors, including installation, measurement variability, and decision-making processes in the construction field. Thus, the connection between field-based practical challenges and laboratory material performance remains insufficiently addressed. To narrow this gap, the present study adopts a holistic approach of both questionnaire-based surveys of construction-sector stakeholders and experimental analysis of PUF insulation behavior. Statistical analyses, including descriptive statistics, correlation analysis, and stepwise multiple regression, are employed to identify key factors influencing insulation material selection and application [9,10]. Subsequently, experimental investigations are conducted to characterize the physical, mechanical, and thermal properties of PUF specimens developed based on field-derived insights. This integrated approach directly links field-based problem identification with laboratory-scale material assessment, contributing to the refinement of PUF production processes and the development of roof insulation systems with enhanced physical, mechanical, and thermal reliability for practical engineering applications. To the best of the authors' knowledge, this study represents one of the first attempts to integrate field-based decision-making analysis with experimental characterization of PUF insulation, thereby establishing a direct and systematic link between practical construction requirements and material performance.

2.0 METHODOLOGY

2.1 Survey Design and Sampling

Survey Design: The questionnaire examined participants' concerns related to roofing insulation. Data collection was divided into three main sections. The first section collected demographic information, including age, gender, occupation, and work experience. The second section, entitled "Opinions on Thermal Insulation Materials," addressed issues related to utilization, ease of installation, market price, cost-effectiveness, and preferred insulation types. The third section, "Additional Suggestions," consisted of open-ended questions that allowed respondents to provide ideas and recommendations for product improvement. To ensure accuracy and content validity, the questionnaire was reviewed by subject matter experts, and the relevance of each item to the research objectives was evaluated using the Index of Item–Objective Congruence (IOC).

Sampling: For populations of unknown size, Cochran's formula was applied to estimate the required sample [11], as shown in Equation (1). The sample size was determined using a 95% confidence level, where Z represents the corresponding value (1.96), e denotes the margin of error (0.05), and P is the estimated population proportion. A value of P = 0.5 was selected to reflect maximum variability. To validate the questionnaire, a pilot study involving 30 participants was conducted [12]. Feedback from this group was used to improve clarity and overall suitability. The reliability analysis indicated excellent internal consistency, with Cronbach's alpha coefficient of 0.957. The survey results were subsequently used as input variables for statistical modeling and experimental design.

$$n_0 = \frac{z^2 p(1-p)}{e^2} = \frac{1.96^2 0.5(1-0.5)}{0.05^2} = 385 \text{ participants} \quad (1)$$

2.2 Statistical Analysis

Statistical analyses were performed using Minitab (Version 22.4 Trial). Descriptive statistics summarized respondent characteristics and overall satisfaction with thermal insulation. All respondents were required to mark the importance based on their perspective for each statement in this section using a five-point Likert scale: 1—not important; 2—slightly important; 3—moderately important; 4—very important; and 5—extremely important [13]. Pearson's correlation analysis examined relationships between satisfaction and material choice, while independent *t*-tests and one-way ANOVA compared responses across demographic groups and usage conditions at a statistical significance level of $\alpha = 0.05$. Regression analysis was then applied to identify key determinants of insulation material use, with stepwise multiple regression employed to systematically identify and retain only statistically significant predictors, thereby improving model parsimony and interpretability. As shown in Equation (2), Y'_i represents the predicted value, a is the intercept, b_1–b_k are regression coefficients, and x_1–x_k are predictor variables. The regression analysis was conducted under the assumptions of linearity, independence, normality of residuals, and homoscedasticity, with multicollinearity among predictors examined prior to model estimation.

$$Y'_1 = a + b_1x_1 + b_2x_2 + \ldots + b_kx_k \quad (2)$$

2.3 Experimental Procedure

The experimental parameters and processing conditions were selected based on key factors identified from the survey and regression analysis, enabling direct validation of field-identified issues through controlled laboratory testing. All experiments were conducted at ambient conditions (25 ± 2°C, relative humidity 50 ± 5%).

2.3.1 Manufacturing Process Forming

PUF insulation specimens were fabricated using a closed mold process with molds produced by 3D printing. Polymerization was initiated through high-speed mixing of polyol with additives, followed by the addition of isocyanate. After which the reactive mixture was injected into a closed mold. Foaming and expansion occurred as the reaction proceeded, filling the mold cavity. As shown in Figure 1, the PUF was cured at room temperature to achieve structural stabilization. After curing, the specimens were demolded, cut, and polished to standard dimensions.

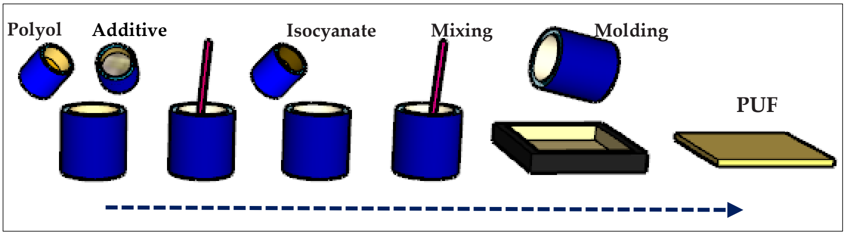


Figure 1: Manufacturing process of PU foam insulation

2.3.2 Sample Preparation

The preparation of PUF samples is shown in Figure 2. The mold was cleaned to facilitate demolding. Polyol was first mixed with additives and stirred at 2,400 rpm for 1 min, followed by the addition of isocyanate and mixing at the same speed for 20 s to initiate polymerization. The reactive blend was immediately injected into a closed mold, where foaming and curing proceeded for 30 min. After expansion and solidification, the samples were demolded, sawn, and cut into standard specimens for testing.

2.3.3 Characterization

The mechanical and thermal characterization of the PUF insulation specimens is tested in accordance with relevant standards.
Hardness: Following ASTM D2240. Using the Shore A durometer, specimens of 50 mm × 50 mm × 25 mm, three specimens per sample.
Density: Following ASTM D3574 (Test A), specimen of 50 mm × 50 mm × 25 mm, three specimens per sample. Three specimens per sample.
Tensile Strength: Following ASTM D3574 (Test E). Dumbbell-shaped specimens with a thickness of 6 mm and a speed of 3 mm/min, three specimens per sample.
Water Absorption: Following ASTM D570-88, specimen of 50 mm × 50 mm × 25 mm, three specimens per sample.
Thermal Characteristics: Following ASTM C518 and ISO 8301. FOX 200 is machine heat flow meter from TA Instruments with ISO 8301. Specimens of 50 mm × 50 mm × 25 mm, three specimens per sample.

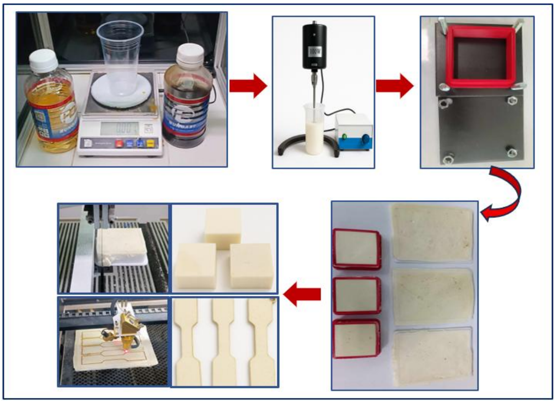
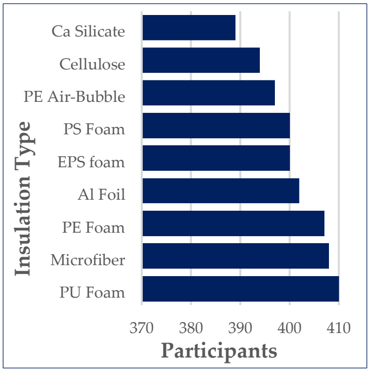


Figure 2: Sample preparation process for polyurethane foam

3.0 RESULTS

3.1 Descriptive Analysis

A questionnaire survey was conducted with 413 construction divisions responsible for thermal insulation, exceeding the minimum required sample size of 385, to identify the types of insulation materials previously used in roofing applications. The results indicated the utilization of nine distinct insulation materials, which were classified into two main clusters: foam-based and non-foam insulation systems. Among the foam-based materials, PU, PE, EPS, and PS were identified, with PUF emerging as the most frequently applied material, as shown in Figure. 3. PUF is favored due to its combination of low thermal conductivity, lightweight nature, and strong adhesion to roofing substrates consistent with those of Deraman et al. and Dukarska et al. [1, 2]. Given its extensive practical adoption, the present study focuses on mechanical and thermal performance of the PUF insulation. Compared with the alternative insulation materials, reported by Onaifo et al. [3], PUF exhibits superior thermal resistance while maintaining sufficient mechanical stability under service conditions, rendering it particularly suitable for roofing insulation applications. Accordingly, PUF was selected as the material of interest in this study.



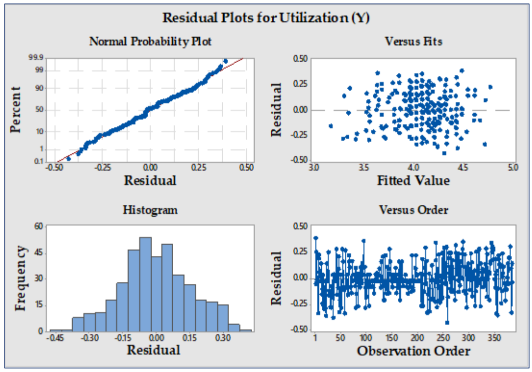


Figure 3: Popularity of insulation type. Figure 4: The residual analysis plots

3.2 Correlation Analysis

The results of Pearson correlation coefficients have moderate to strong positive correlations between factors influencing roofing thermal insulation material selection, with the highest correlation between Y and X_2 at 0.62. This suggests cost-related factors drive decision-making. The selection process is multidimensional, as Y and X_1 and X_3 indicated significant correlations (0.53 and 0.61, respectively). As shown in table 1, gender differences in all factors were statistically significant by independent samples T-test. Demographics also affected utilization, installation, and market price, according to ANOVA. Analysis showed a significant relationship between age and utilization, price, and market. Job position relates to utilization, price and market, and cost-effectiveness. Years of experience also affected utilization and cost-effectiveness. All results that were significant at $\alpha = 0.05$ are shown in Table 2. These results are consistent with those of Zaidi et al. [5], who found that cost-effectiveness and energy efficiency have a direct impact on the selection of roofing insulation systems and show a positive correlation with both financial investment and thermal performance. Among all factors, price and market (X_2) considerations exhibited the strongest association with utilization, indicating their dominant role in decision-making. The positive correlation between insulation utilization and price and market factors suggests that considerations are a key determinant in roofing insulation material selection.

Table 1: Pearson correlation coefficients

Correlations	X1	X2	X3

Y	0.53**	0.62**	0.61**
X1		0.57**	0.38**
X2			0.54**

** Correlation is significant at the 0.05 level (2-tailed)

Table 2: Relationship of age, position, and experience with factors

Factors	Age		Position		Experience		Gender	
	F	P-value	F	P-value	F	P-value	T-test	P-value
Utilization (Y)	2.991	0.019*	7.861	0.000*	5.398	0.000*	-2.141	0.033*
Installation (X_1)	2.155	0.073	1.734	0.089	1.409	0.220	-2.358	0.019*
Price and Market (X_2)	3.083	0.016*	6.449	0.000*	3.196	0.008*	-2.129	0.034*
Cost-effectiveness (X_3)	1.934	0.104*	6.449	0.000*	1.460	0.202	-0.255	0.799

* Relationship is significant at the 0.05 level (2-tailed)

3.3 Regression Analysis

The residuals exhibit random dispersion with respect to fitted values and observation order, indicating homoscedasticity and independence, as shown in Figure 4. Stepwise multiple regression analysis, shown in Table 3, identified installation ease (X_1), price and market factors (X_2), and cost-effectiveness (X_3) as significant positive predictors of thermal insulation utilization (Y). The model explains 70.3% of the variance ($R^2 = 0.703$), indicating strong explanatory capability. All predictors were statistically significant at $p < 0.05$, suggesting that economic and practical considerations play a dominant role in roofing insulation selection.

Table 3: Results of stepwise multiple regression analysis

Model	B	SD.	t	P-value
Constant	1.050	0.113	10.180	0.000
X_1	0.209	0.027	7.800	0.000
X_2	0.287	0.029	10.040	0.000
X_3	0.249	0.021	12.010	0.000
R^2=0.703			SE=0.157	F=300.580

These findings are consistent with previous studies by Ali and Anwar's [10], which highlight the strong influence of price-related factors on insulation adoption decisions. Nevertheless, the results reflect associative relationships rather than causal effects. The regression model presented in Equation (3) indicates that installation ease (X_1), price and market factors (X_2), and cost-effectiveness (X_3) each contribute positively to the utilization of roofing insulation materials (Y). X_2 has the largest standardized and statistically significant coefficient, while X_1 and X_3 exhibit smaller but meaningful effects.

$$Y = 1.050 + 0.209X_1 + 0.287X_2 + 0.249X_3 \quad (3)$$

3.4 Characterization of PUF Properties

All mechanical and thermal tests were conducted in triplicate, and the results are reported as mean values with corresponding standard deviations. Figures 6–8 and Table 4 show results and comparative analysis of the mechanical and thermal properties of the synthesized PUF. The hardness was measured at 70 ± 1.0 Shore A, which is higher than the flexible PUF value reported by Rossi et al. [14], indicating a semi-rigid PUF structure. This characteristic is advantageous for roofing insulation systems, as the flexibility allows the material to accommodate building movement and thermal expansion. The measured density of 97 ± 14.6 kg/m^3 lies within the range reported by Onaifo et al. and Rossi et al. [3, 14], suggesting that the closed-cell morphology of the synthesized foam is comparable to that of conventional insulation foams. The water absorption of the sample (9 ± 1.5%), is consistent with the value reported by Dukarska et al. [2], indicating adequate resistance to moisture under humid conditions, which is particularly important for roofing applications exposed to the environment. The tensile strength had a value of 680 ± 20.3 kPa, and the corresponding stress–strain response exhibited an initial elastic region followed by abrupt failure. This value is higher than those reported by Onaifo et al. and Rybarek et al. [3, 6], indicating improved mechanical performance. The stress–strain behavior, characterized by elastic deformation followed by sudden fracture, is polymeric foam designed for load-bearing insulation applications. Thermal analysis, DSC, revealed an endothermic peak at 330.83°C, with onset and end-set temperatures of 293.28°C and 364.59°C, respectively. The total energy absorption was 444.15 mJ (293.94 J/g). The thermal conductivity of the foam was measured as 0.054 ± 0.0052 W/(m·K). The thermal stability indicated by the DSC results was higher than that reported by Rybarek et al. [6], whose materials exhibited decomposition temperature range of 225-300°C. The higher decomposition temperature suggests enhanced resistance to thermal deterioration, indicating a strongly hydrogen-bonded and crosslinked PUF, in accordance with recent literature on the intrinsic thermal stability of semi-rigid PUF under inert conditions. Furthermore, the measured thermal conductivity agrees well with the results reported by Olcay and Kocak [4] and Soloveva et al. [16], confirming that this PUF maintains effective thermal insulation performance. Despite these favorable results, the present analysis is limited to laboratory-scale testing, and further studies are required to evaluate long-term durability and performance under real roofing service conditions.

Table 4: Results PUF testing and comparison

Testing	Results	Comparisons
Hardness (shore A)	70 ± 1.0	50-60 [14]
Density (kg/m³)	97 ± 14.6	71 and 100 [3,15]
Tensile Strength (kPa)	680 ± 20	220 and 393 [3,6]
Water Absorption (%)	9 ±1.5	10 [2]
Thermal Conductivity (W/(m·K))	0.054± 0.0052	0.045 - 0.055 and 0.051 [4,16]
Thermal Degradation: T_{Max} (°C)	330	225 [6]

(a) (b) (c)

Figure 6: The PUF testing (a) hardness, b) tensile and c) thermal conductivity

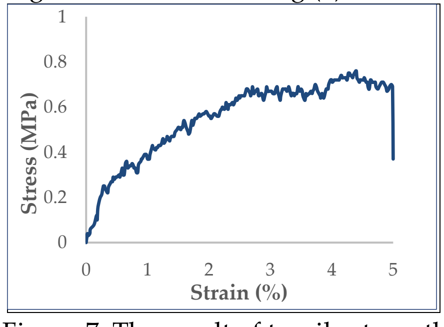


Figure 7: The result of tensile strength

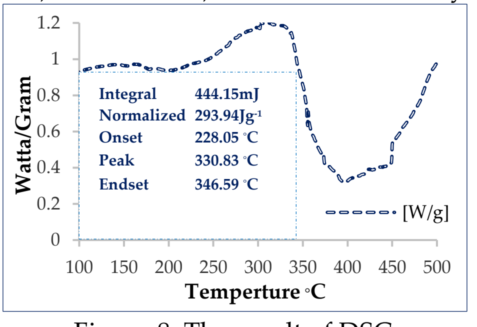


Figure 8: The result of DSC

4.0 CONCLUSIONS

This study confirms that PUF is the most widely applied roofing insulation material, primarily due to its favorable thermal performance, ease of installation, and cost-effectiveness. The statistical results indicated significant Pearson correlations among the key decision factors, while the regression model satisfied all fundamental assumptions, including the normality of residuals, confirming the model's robustness and reliability. Stepwise multiple regression analysis indicated that installation ease, market price, and cost-effectiveness are the most influential factors governing the selection and utilization of roofing insulation materials. These results reflect practical decision-making behavior in construction projects, where economic and constructability considerations are closely intertwined. The fabricated PUF was subjected to comprehensive material characterization. The hardness of the PUF was lower than typical reference values, leading to a comparatively softer structure. Consistently, indicating improved tensile strength and maintaining a relatively low density. Thermal analysis indicated improved thermal stability based on DSC results. Moreover, the thermal conductivity remained within the typical range, supporting the suitability of the developed PUF for roofing insulation applications. Overall, the present study integrates statistical modeling with experimental evaluation to relate field-based decision factors to material performance. The results meet the stated research objectives and provide useful guidance for PUF formulation, process optimization, and practical implementation in roofing systems. Future research should focus on long-term durability, environmental safety, and the development of sustainable PUF formulations using recycled or renewable resources to further improve insulation performance.

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AUTHOR CONTRIBUTIONS

S. Kaewjang: Conceptualization, Methodology, Writing—Original Draft Preparation; T. Ratanawilai: Data Curation, Validation, Supervision; Z. Mustafa: Validation, Writing-Reviewing, and Editing.

CONFLICTS OF INTEREST

The manuscript has not been published elsewhere and is not under consideration by other journals. All authors have approved the review, agree with its submission, and declare no conflict of interest in the manuscript.

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