Marek HRYNIEWICZ* ORCID: 0000-0001-9926-699X

Department of Economical and Energetical Analyses, Institute of Technology and Life Sciences – National Research Institute, Falenty, Al. Hrabska 3, 05-090 Raszyn, Poland

* author e-mail: m.hryniewicz@itp.edu.pl

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MATHEMATICAL ANALYSIS OF MECHANICAL AND THERMAL PROPERTIES OF HEMP SHIVE-BASED COMPOSITES – REGRESSION MODEL FITTING

ANALIZA MATEMATYCZNA WŁAŚCIWOŚCI MECHANICZNYCH I TERMICZNYCH KOMPOZYTÓW NA BAZIE PAŹDZIERZY KONOPNYCH – DOPASOWANIE MODELU REGRESJI

***Summary**: This study investigates the dependencies between mechanical and thermal characteristics of hemp shive-based composite. The composites of this type are becoming popular because they are environmentally friendly, provide good thermal insulation, and have strong mechanical properties, serving as a viable alternative to traditional building materials. The research analyzes how these materials conduct heat and withstand pressure, using different ratios of hemp shive to binder. To predict the behavior of the mentioned materials, three mathematical models were applied: linear, quadratic, and exponential. The study has determined that linear models are the most effective for practical applications, as they have high R^2 values, indicating a good fit with the data. A strong correlation was found between thermal conductivity and compressive strength, which helps in improving composite designs. The results endorse the use of hemp-based composites in construction, highlighting their ability to balance thermal efficiency, mechanical strength, and environmental sustainability. The study suggests more research to explore alternative binders, assess long-term durability, and evaluate the feasibility of large-scale production.*

***Keywords**: hemp composite, mathematical modeling, regression modeling, sustainable construction*

Streszczenie: W pracy zbadano zależności pomiędzy właściwościami mechanicznymi i termicznymi kompozytu na bazie paździerzy konopnych. Kompozyty tego typu cieszą się coraz większą popularnością, ponieważ są przyjazne dla środowiska, zapewniają dobrą izolację termiczną i posiadają dobre właściwości mechaniczne, stanowiąc realną alternatywę dla tradycyjnych materiałów budowlanych. W badaniu analizowano, w jaki sposób te materiały przewodzą ciepło i wytrzymują ciśnienie, stosując różne proporcje paździerzy konopnych do spoiwa. Do przewidywania zachowania tych materiałów zastosowano trzy modele matematyczne: liniowy, kwadratowy i wykładniczy. W badaniu ustalono, że modele liniowe są najskuteczniejsze w zastosowaniach praktycznych, ponieważ mają wysokie wartości R^2, co wskazuje na dobre dopasowanie do danych. Stwierdzono silną korelację między przewodnością cieplną a wytrzymałością na ściskanie, co pomaga w ulepszaniu projektów kompozytów. Wyniki potwierdzają zastosowanie kompozytów na bazie konopi w budownictwie, podkreślając ich zdolność do równoważenia wydajności cieplnej, wytrzymałości mechanicznej i zrównoważenia środowiskowego. Badanie sugeruje dalsze badania w celu zbadania alternatywnych spoiw, oceny długoterminowej trwałości i oceny wykonalności produkcji na dużą skalę.

Słowa kluczowe: kompozyt konopny, modelowanie matematyczne, modelowanie regresyjne, budownictwo zrównoważone

Introduction

Growing concerns about environmental impacts and increases in building performance have shifted construction industry interests toward sustainable materials [1, 2]. Hemp composites, and specifically those based on hemp shives (the woody core of the hemp plant), have attracted attention because of their good mechanical and thermal properties [3, 4, 5]. Ecofriendly material replacements that are renewable can be a substitute of the traditional construction elements which would correspond to the global sustainable development views and objectives [6].

Hemp shives have a high porosity, which results in good thermal insulation characteristics. The thermal conductivity of materials based on hemp shive is found to vary between 0.090–0.160 W/(m·K), with a slight increase in value occurring with increasing material density [7]. The intrinsic porosity not only improves thermal insulation by counteracting heat transfer but also causes sound installation characteristics [8].

Hemp composites exhibit good mechanical properties which are impacted by the size of the shives and the binder used. The previous studies indicated that composites based on fine shives resulted in a higher mechanical strength than composites based on coarser shives [7, 9, 10]. Also, the setting and properties of the material largely depend on the binding–matrix relationship, which occurs in the binder and hemp particles [11, 12]. Example: An air lime-based binder has also been linked with enhanced mechanical properties of hempcrete [1, 8, 11].

Apart from mechanical and thermal properties, hemp composites are showing interesting hygrothermal properties [13, 14, 15]. The material is a way of moisture regulation, which plays a role in indoor air quality and occupant satisfaction [16, 17, 18, 19, 20]. Because of this feature, as well as its thermal performance, hemp-based composites are used in energy-efficient building solutions [4, 21].

Then again, the composite materials could be famous at the integration of hemp shives which ensures sustainability of building [22]. This relation is essential as it can bridge together the physical properties of hemp shives, the selection of binders, and the processing parameters to formulate sustainable materials with high mechanical and thermal performance.

Understanding the interplay between mechanical and thermal properties is crucial in materials engineering, as it influences the performance and reliability of materials under various operational conditions [3]. Mechanical properties, such as strength, elasticity, and toughness, dictate a material's ability to withstand forces without deformation or failure. Thermal properties, including thermal conductivity, determine how a material responds to temperature changes, affecting its ability to conduct heat or store thermal energy [6]. For designers, mathematical dependencies between the amounts of raw materials included in the composite and its physical properties are important. These relationships allow the composition of the composite to be formulated in relation to the mechanical (e.g. compressive strength) and thermal requirements (e.g. thermal conductivity coefficient). Moreover, the mathematic relationship can be found between the compressive strength and thermal conductivity coefficient. This relationship is useful for designing the hemp – binder composition with taking into account not only the physical parameters of the composite but also the prices of its components and its total carbon footprint. Such composite carbon footprint is negative according to [23, 24] due to hemp shives' content. The relationship is as follows: the more hemp shives, the greater the negative carbon footprint of the composite. However, mechanical and thermal properties of the composite are changing due hemp shives content. The construction material should meet durability requirements. The aim of the present work is to analyze the mathematical relationships between mechanical and thermal parameters according to the proportions of hemp shives and lime binder.

Materials and methods

Brzyski [25] investigated different properties of hemp composite consisting of hemp shives and lime binder in different proportions and with different materials grouped in series. The results of Series 1 where lime binder was modified by addition of 15% concrete type CEM II/B-V 32,5R and 15% metakaolinite are specially interesting for the analysis. Table 1 presents the component content.

Table 1. Components' content

Component	S1.1	S1.2	S1.3	S1.4
Water (kg/m³)	394.1	373.0	351.9	330.8
Hemp shives K1 (kg/m³)	140.8	140.8	140.8	140.8
Metakaolin (kg/m³)	42.2	38.6	35.3	31.7
Cement CEM II/B-V 32.5R (kg/m³)	42.2	38.6	35.3	31.7
Hydrated lime (kg/m³)	197.1	180.3	164.5	147.8

Source: Brzyski [25]

Table 2. The thermal conductivity coefficient according to weight proportions of hemp shives: binder

Weight proportions of hemp shives: binder	Thermal conductivity coefficient (W/m K)		
	Minimum	Average	Maximum
1:2	0.1190	0.1220	0.1250
1:1.83	0,1090	0.1130	0.1170
1:1.67	0.0975	0.1010	0.1045
1:1.5	0.0848	0.0880	0.0912

Source: own elaboration based on Brzyski [25]

Table 3. The compressive strength according to weight proportions of hemp shives: binder

Weight proportions of hemp shives: binder	Compressive strength (MPa)		
	Minimum	Average	Maximum
1:2	0.305	0.32	0.335
1:1.83	0.272	0.29	0.308
1:1.67	0.243	0.26	0.277
1:1.5	0.214	0.23	0.246

Source: own elaboration based on Brzyski [25]

Table 2 presents the thermal conductivity coefficient according to weight proportions of hemp shives: binder. Table 3 presents the compressive strength according to weight proportions of hemp shives: binder.

There will be fitted to data the following mathematical models: linear, quadratic and exponential. Also, a linear model will be fitted to determine the dependence between the thermal conductivity coefficient and compressive strength.

Results

Table 4 presents fitting results. All models show very high coefficients of determination. However, the linear models could be the best in practical use.

Table 2. The thermal conductivity coefficient according to weight proportions of hemp shives: binder

Model	Thermal conductivity coefficient (hemp shives)
Linear, R^2	$y=0.0679 \cdot x-0.0147$, $R^2=0.9696$
Quadratic, R^2	$y=-0.0416 \cdot x^2+0.2119 \cdot x-0.1380$, $R^2=0.9786$
Exponential, R^2	$y=0.0319 \cdot \exp(0.6721 \cdot x)$, $R^2=0.9562$
Model	**Compressive strength (hemp shives)**
Linear, R^2	$y=-0.0412+0.1807 \cdot x$, $R^2=0.9999$
Quadratic, R^2	$y=-0.0412+0.1807 \cdot x+0.0000 \cdot x^2$, $R^2=0.9999$
Exponential, R^2	$y=0.0856 \cdot \exp(0.6625 \cdot x)$, $R^2=0.9973$
Model	**Thermal conductivity coefficient (Compressive strength)**
Linear, R^2	$y=14.2736 \cdot x+0.2618$, $R^2=0.9696$

Source: own elaboration

Summing up

The study highlights a growing interest in eco-friendly building materials like hemp composites. Hemp shives, small particles of hemp, provide a low thermal conductivity and strong mechanical strength, making them a viable alternative to traditional building materials. Additionally, they offer environmental benefits with a negative carbon footprint.

The study employs various mathematical models — linear, quadratic, and exponential — to accurately predict the thermal conductivity and compressive strength of these materials. These models are reliable in forecasting material properties.

A strong correlation was identified between thermal insulation and compressive strength using a linear model, aiding in the design of materials that effectively balance heat retention and structural strength.

Guidelines for developing hemp-lime composites are provided, focusing on mechanical and thermal performance. Mathematical predictions assist engineers in selecting materials by weighing factors like cost-effectiveness and sustainability.

Future research could investigate:

- The impact of different binders and additives on performance.
- The long-term durability and moisture resistance of hemp-based materials.
- Methods to scale up production while preserving sustainability benefits.

The study confirms that hemp composites are a sustainable choice for construction, offering a balance of thermal efficiency, mechanical strength, and low environmental impact.

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