INFLUENCE OF PARTICLE SIZE AND PROPORTION OF AQUATIC PLANT FRACTIONS ON THERMAL CONDUCTIVITY OF BIOCOMPOSITE INSULATION MATERIALS

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Abstract. This study examines the impact of the particle size and proportion of crushed aquatic plants – common reed (*Phragmites australis*) and bulrush (*Scirpus lacustris*) – on the thermal conductivity coefficient of a composite insulation material. Carrageenan, a natural polysaccharide derived from seaweed, is used as an adhesive to create a sustainable, eco-friendly alternative to conventional insulation materials. The composite's thermal performance is influenced by the thermal conductivity properties of each component, as well as the distribution and size of the plant particles. Samples were prepared with varying particle size fractions and proportions to assess their effect on packing density, porosity, and heat transfer. Thermal conductivity was measured using steady-state methods, and microstructural analysis was performed to evaluate particle arrangement and adhesion quality. Initial findings show that finer fractions enhance packing density, reducing void spaces and improving thermal resistance. In contrast, coarser particles create more air-filled voids, potentially increasing insulation performance but reducing structural stability. Carrageenan plays a key role as a binder, affecting both the thermal and mechanical properties of the material. A predictive model was developed to determine the overall thermal conductivity coefficient based on the particle size, proportions, and individual thermal properties. The results confirm the potential of common reed and bulrush as components of biocomposite insulation materials. By optimizing the particle size distribution and composition, it is possible to achieve low thermal conductivity and sufficient mechanical strength. This research supports the development of sustainable insulation solutions using natural and renewable resources.

Keywords: thermal conductivity, particle size distribution, sustainable insulation, eco-friendly materials.

Introduction

The growing demand for sustainable construction materials has driven research into bio-based insulation solutions that reduce environmental impact while maintaining effective thermal performance. Traditional insulation materials, such as mineral wool and polystyrene, often pose ecological concerns due to their energy-intensive production and limited biodegradability. In response, natural fibre composites have emerged as a promising alternative, offering renewable, biodegradable, and energy-efficient options for thermal insulation applications.

This study explores the development and characterization of a composite insulation material incorporating crushed aquatic plants – common reed (*Phragmites australis*) and bulrush (*Scirpus lacustris*) as the primary filler. These fast-growing plants are abundant in wetland ecosystems and have been identified as potential renewable resources for bio-based insulation. To ensure cohesion and structural integrity, carrageenan, a natural polysaccharide extracted from seaweed [1], is used as a binder, providing an environmentally friendly alternative to synthetic adhesives. Biopolymers like carrageenan and starch are often used as binding agents in bio-composites, enhancing their thermal and mechanical performance. Starch-based matrices, combined with natural fibers like hemp and date palm, achieve low thermal conductivities between 0.051-0.058 $W \cdot (m \cdot K)^{-1}$ [2]. Additionally, silica-reinforced biocomposites exhibit even lower thermal conductivities, around 0.0242 $W \cdot (m \cdot K)^{-1}$, demonstrating the potential of hybrid materials for superior insulation [3].

The research focuses on the influence of the particle size distribution and composition on the thermal conductivity of the developed biocomposite. Since thermal performance is strongly dependent on material microstructure, factors such as the packing density, porosity, and the distribution of air voids within the composite are examined. The study also incorporates a mathematical model for heat transfer analysis, applying a numerical approach to evaluate the impact of variable thermal conductivity across different material layers.

To validate the theoretical framework, a prototype insulation sample was fabricated and subjected to thermal conductivity measurements using steady-state methods. Experimental results were compared with numerical predictions to assess the accuracy of the model and determine the optimal particle size fraction and composition for improved thermal insulation properties.

By integrating mathematical modelling, numerical simulations, and experimental testing, this work contributes to the ongoing development of sustainable insulation materials. The findings highlight the potential of aquatic plant-based composites as viable alternatives to conventional insulation, offering both thermal efficiency and environmental benefits.

The use of renewable bio-composite materials in construction is of great importance. It reduces the burden on nature, uses less resources, and is more environmentally friendly than man-made materials.

Many scientific experiments have been conducted to investigate various bio-composite materials. The main characterization parameter of these materials is thermal conductivity. The heat conductivity is significantly influenced by such factors as: the size of the fraction of biomaterials (of plant origin), the orientation of fractions relative to the direction of heat spread, the presence and size of air pores, and the composition of the binder.

The list of plant substances used to create bio-composite materials is long, but some materials are considered, which are used as a base for bio-composites. Review of studies [4] of bio-based composite materials shows that the reviewed paper thermal conductivity of moss fibers (0.034 $W \cdot (m \cdot K)^{-1}$), wood fibers (0.043 $W \cdot (m \cdot K)^{-1}$), wheat straw (0.046 $W \cdot (m \cdot K)^{-1}$), and corn husk fibers (0.046 $W \cdot (m \cdot K)^{-1}$) is the most promising solution for energy efficiency in the construction industry.

Good results were achieved on panels of moss and reed with a thermal conductivity of 0.041 to 0.068 $W \cdot (m \cdot K)^{-1}$ and for panels of moss and straw with a thermal conductivity of 0.044-0.046 $W \cdot (m \cdot K)^{-1}$ [5]. The study of mixing a mass fraction of 60% of cardboard waste and 40% of reed fibers shows a thermal conductivity 0.082 $W \cdot (m \cdot K)^{-1}$ and mixing a mass fraction of 60% of cardboard waste and 40% of straw fibers shows a thermal conductivity 0.080 $W \cdot (m \cdot K)^{-1}$ [6]. The same results of the thermal conductivity 0.082 $W \cdot (m \cdot K)^{-1}$ were obtained for the composite based on cardboard waste and reed fibers [7].

Cereal straw has been widely studied in various applications, its thermal and mechanical properties are well suited for various applications [8]. A composite made from coir mixed with sugarcane bagasse (1.0 mm particle size) demonstrated a thermal conductivity of 0.01467 $W \cdot (m \cdot K)^{-1}$ [9]. A hybrid composite consisting of S-glass fiber, epoxy resin, and sugarcane bagasse waste fiber (Sugarcane Bagasse Fiber-Reinforced Epoxy Composites) showed a thermal conductivity of 0.166 $W \cdot (m \cdot K)^{-1}$ [10]. Using auto-coherent homogenization, the thermal conductivity of sugarcane bagasse fibers reinforcing cement composites was estimated to be 0.110 $W \cdot (m \cdot K)^{-1}$ [11]. Thermal conductivities of straw bales (average density about 100 $kg \cdot m^{-3}$) for various combinations of straw mass are in the range 0.086 - 0.097 $W \cdot (m \cdot K)^{-1}$ [12].

Other studies on composite biomaterials show low thermal conductivity values, indicating that these materials are very advantageous to use in construction. For example, the research of low-environmental-impact bio-insulation fiberboards from bamboo fibers and protein-based bone glues shows good results. The thermal conductivity is in the range 0.0582-0.0812 $W \cdot (m \cdot K)^{-1}$ [13]. The study on bio-composite boards based on different fraction fibre hemp shivs as an aggregate and corn starch as a binding material for thermal insulation applications shows that the lowest thermal conductivity is obtained for the fraction 2.5/5 mm, that is in the range of 0.0605-0.0630 $W \cdot (m \cdot K)^{-1}$ [14]. Thermal studies and microstructure of date palm tree surface fibers (DPSF) reveal that they could be used as a new building insulation material. Thermal conductivity is measured for four different densities and the results show that the minimum and maximum values are 0.0475 and 0.0697 $W \cdot (m \cdot K)^{-1}$, respectively [15]. Bio-composites of sheep wool embedded in a polymer matrix were prepared by freeze-drying, combining soy protein with 7, 10, 15 and 20 wt.% sheep wool and thermal conductivity characterization showing values in 0.045-0.055 $W \cdot (m \cdot K)^{-1}$ range [16].

Based on the data obtained from various sources, we can conclude that the thermal conductivity range is 0.034-0.166 $W \cdot (m \cdot K)^{-1}$. Moreover, the higher the value of the bio-composite material density, the higher the thermal conductivity.

Materials and methods

The methodology of the study includes the formulation of a mathematical model, the implementation of a variable heat transfer coefficient, the definition of initial and boundary conditions, the discretization of the governing equation, development of a computational code for simulation and analysis and numerical experiments. The model was first tested assuming a constant thermal conductivity coefficient. Subsequently, heat transfer was simulated in a composite material consisting of: (1) three regions with different thermal conductivities, and (2) a finely divided structure with spatial variation in thermal conductivity. Following the modelling, a sample of a thermal insulation material was fabricated, composed of approximately 3 cm long pieces of lake bulrush, supplemented with around 30% finely ground bulrush particles (1–5 mm in size), which effectively filled the gaps between the larger fragments. The entire structure was bonded using a carrageenan-based adhesive.

A well-established mathematical model of heat transfer was employed as the foundation, wherein the coefficient of the spatial derivative of temperature was treated as a function of position. This approach inherently increases the complexity of the difference equation; however, it simultaneously enables the incorporation of variable thermal conductivity across different segments of the one-dimensional material, thereby enhancing the model's adaptability to spatially heterogeneous thermal properties.

$$\begin{cases} \dfrac{\partial T}{\partial t} = \dfrac{\partial}{\partial x}\left(k(x)\cdot\dfrac{\partial T(x,t)}{\partial x}\right) + F(x,t), \;\; 0 \le x \le l, \; 0 < t \le time \\ T(x,t)\big|_{t=0+0} = u_0(x), \;\; 0 \le x \le l \\ \left.\dfrac{\partial T(x,t)}{\partial x}\right|_{x=0+0} = u_1(t), \;\; 0 < t \le time \\ \left.\dfrac{\partial T(x,t)}{\partial x}\right|_{x=l-0} = u_2(t), \;\; 0 < t \le time \end{cases} \tag{1}$$

where T – desired temperature distribution function;
t – time variable;
x – spatial variable;
F – external influence function (heater);
l – boundary limit of 1D space;
$time$ – temporal boundary limit;
u_0 – initial condition function;
u_1 – boundary condition function at the beginning of the 1D space;
u_2 – boundary condition function at the end of the 1D space.

First, we perform mathematical transformations (2) for the derivative of the product of two functions:

$$\frac{\partial T(x,t)}{\partial t} = \frac{\partial k(x)}{\partial x}\cdot\frac{\partial T(x,t)}{\partial x} + k\cdot\frac{\partial^2 T(x,t)}{\partial x^2} + F(x,t). \tag{2}$$

A 4-point stencil (Fig. 1), which, when moved across the modelled domain, is used to compute the vertex value at each step. The values in the lower layer are known from the initial/boundary conditions or previously computed layers.

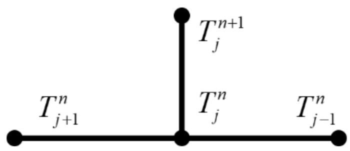

Fig. 1. **4-point stencil**

A discrete equation was developed for the numerical solution of the main equation of the mathematical problem of heat transfer - a partial differential equation. Substitutions (3) of continuous derivatives with finite differences were applied:

$$\frac{\partial T}{\partial t} \approx \frac{T_j^{n+1} - T_j^n}{\Delta t}, \quad \frac{\partial k}{\partial x} \approx \frac{k_{j+1} - k_j}{\Delta x}, \quad \frac{\partial T}{\partial x} \approx \frac{T_{j+1}^n - T_j^n}{\Delta x}, \quad \frac{\partial^2 T}{\partial x^2} \approx \frac{T_{j+1}^n - 2T_j^n + T_{j-1}^n}{\Delta x^2}. \tag{3}$$

We obtain the following (4) discretized expression:

$$\frac{T_j^{n+1} - T_j^n}{\Delta t} = \frac{k_{j+1}\cdot\left(T_{j+1}^n - T_j^n\right) - k_j\cdot\left(T_{j+1}^n - T_j^n\right)}{\Delta x^2} + k_j\cdot\frac{T_{j+1}^n - 2T_j^n + T_{j-1}^n}{\Delta x^2} + F_j^n, \tag{4}$$

from which we can express (5) the sought stencil vertex value:

$$T_j^{n+1} = T_j^n \cdot \left(1 - \frac{\Delta t}{\Delta x^2} \cdot \left(k_j - k_{j+1}\right)\right) + \frac{\Delta t}{\Delta x^2} \cdot \left(k_{j+1} \cdot T_{j+1}^n + k_j \cdot T_{j-1}^n\right) + F_j^n. \tag{5}$$

As a result, an expression for calculating the stencil vertex value is obtained. By moving it across the domain, 3D surface points can be derived, describing the sought temperature field in the (x,t) domain, i.e. the heat distribution in the 1D object over time. The next step is to develop a computer code for numerical calculations in the MATLAB environment. To test the method, the external heater function F was first defined as constant at the beginning of the studied segment throughout the simulation time:

$$F(x = 0,\ 0 \le t \le time) = const\,. \tag{6}$$

The first numerical experiment (Fig. 2) is applied to a homogeneous material with a constant heat transfer coefficient $k = 0.05\, W / m \cdot K$. The simulation spans 30 minutes, with the heater applied at the far end of the 1D material. Initially, an exponential temperature increase is observed, followed by a linear stabilization as thermal equilibrium is approached. In the case of composite materials (Fig. 4, 5), the coefficient is applied in the form of a function.

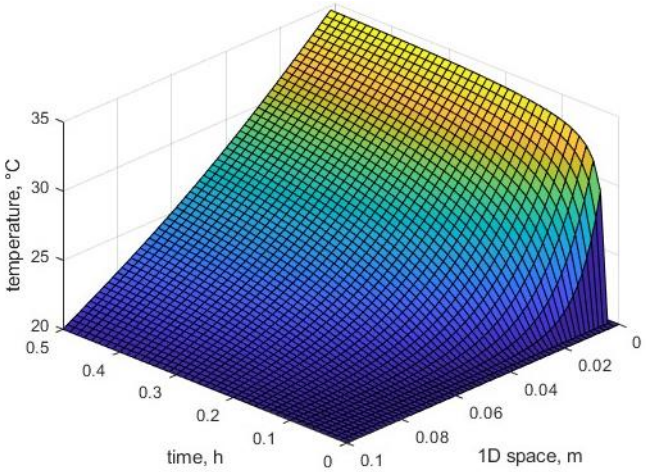

Fig. 2. **Heat transfer in a homogeneous material. A heat flux is observed over time, leading to a uniform temperature distribution at the end of the process**

Results and discussion

A series of numerical experiments have been performed, two of which are presented in this work. The first (Fig.4) simulates the temperature dynamics in a material composed of three components with different heat transfer coefficients. A rapid heat flow is observed at the beginning, then rapid heat propagation, and finally weak heat transfer at the opposite end. In the considered period, which is longer than in the others (Fig.2, Fig. 5), a uniform distribution does not occur. In contrast, in the case of the composition of crushed materials (Fig. 5), where the 1D material is composed of many (13) short sections (Fig. 3) with different heat transfer coefficients, where the base material (bulrush, with k = 0.04 W·(m·K)$^{-1}$) is connected to an adhesive (carrageenan, with k = 0.5 W·(m·K)$^{-1}$), a smoothed heat flow is observed, which ends with a uniform distribution, but reaches a higher temperature on the heater side.

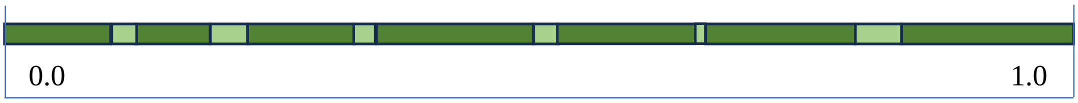

Fig. 3. **1D segment is divided into 13 random sections, where the dark green represents bulrush particles (approximately 80%) and the light green represents the binder material**

The thermal conductivity coefficient k was applied, consisting of 13 random sections, where the parameter corresponding to the bulrush is about 80% of the material length.

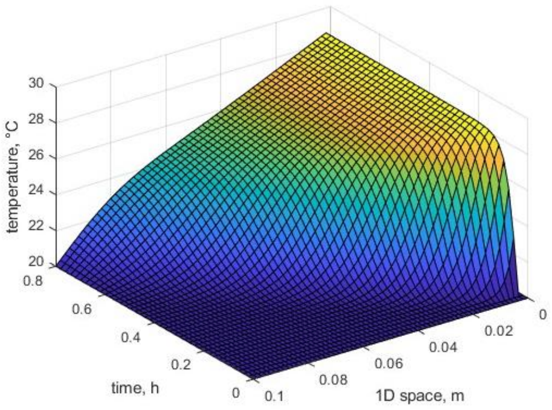

Fig. 4. **Heat transfer in a non-homogeneous material; the material consists of 3 regions with low, high, and low thermal conductivity, leading to varying heat flux and temperature distribution across the domain**

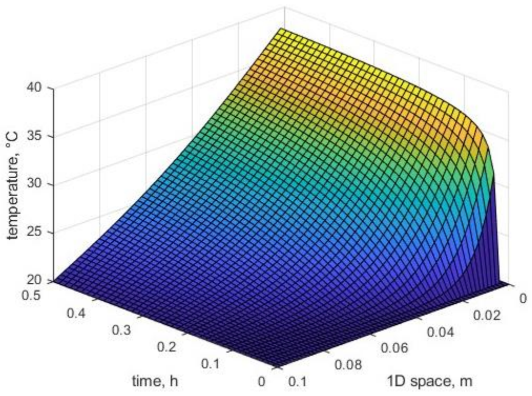

Fig. 5. **Heat transfer in a non-homogeneous material with 13 random distribution of low/high thermal conductivity regions; the temperature reached is higher than in the case of a homogeneous material**

A series of thermal insulation materials were practically manufactured, consisting of variously chopped reeds (*Scirpus lacustris*) – pieces up to 3 cm long, which form the base mass, and finely ground to fill gaps, and a biopolymer adhesive – carrageenan from the seaweed *Furcellaria lumbricalis*, which provides a one-piece structure for the entire material. After mixing, pressing in a mold and drying, heat transfer tests were performed in both increase and decrease modes. For the purposes of the tests, a two-channel chamber (Fig. 6) was constructed, in which the developed material and an industrial thermal insulation material (glass wool) with a known heat transfer coefficient k = 0.04 W·(m·K)$^{-1}$ were installed with identical heaters. One of the developed samples is shown in Fig. 7.

Fig. 6. **Experimental setup for heat transfer tests; the test and reference (glass wool) materials are heated equally, and temperature data is obtained on both sides**

Fig. 7. **Sample of the developed thermal insulation material – crushed reeds with carrageenan adhesive; the pores are filled with fine reed particles**

To compare the developed material with the reference, the temperature differences inside and outside the material were examined. From the graph (Fig. 8) we observe that, for example, in the 500-th data record, the temperature difference for the prototype is 29.45 °C, which is 97.3% of the temperature difference (30.25 °C) for the glass wool sample. Similarly, in the 640-th data record, the efficiency of the prototype reaches 98% of the reference indicator. These results indicate that the thermal insulation performance of the developed biocomposite approaches that of conventional glass wool, demonstrating its potential as a sustainable alternative. The relatively high efficiency can be attributed to the compact structure formed by the optimized particle distribution and the cohesive effect of the carrageenan binder. Moreover, the minimal temperature difference between the prototype and the reference sample across a broad range of data points suggests consistent and stable heat retention properties under dynamic conditions.

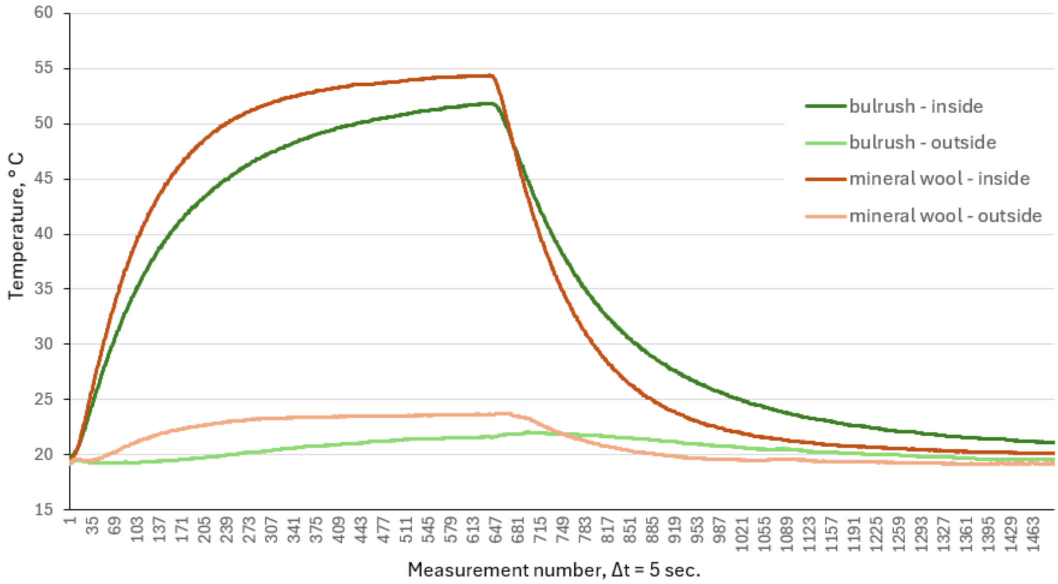

Fig. 8. **Temperatures on the sample surfaces on the heated side and outside with the heater turned on (1-645) and off (646-1473)**

The temperature decrease dynamics with the heater turned off shows a similar picture - high efficiency of the developed thermal insulation material above 90% compared to the reference. This study did not consider the heat capacity of both samples, which has a large effect in dynamic thermal regimes, but not in static operation under conditions of small temperature changes.

The results suggest that the inclusion of fine bulrush particles (1-5 mm) significantly contributes to reduction of the thermal conductivity by effectively filling voids between larger plant fragments, thus limiting convective air movement within the composite. This is supported by observations of other authors [17], who reported that reduced pore size in bio-based composites reduces the thermal conductivity due to suppressed air diffusion. It has also been noted [18] that homogeneity and particle packing density play a crucial role in determining the thermal insulation performance of natural fibre materials. In our case, the use of approximately 30% fine fraction ensured better contact between components and improved microstructural compactness, which likely enhanced the material's thermal resistance. These findings support the conclusion that optimizing the particle size distribution and mass ratio is essential for the development of efficient plant-based insulation materials.

The mathematical model (1) enables accurate simulation of heat transfer within the developed composite material by calibrating the thermal conductivity coefficient to match the temperature values observed in real-time experiments. As demonstrated in Fig. 8, at the time point 580 × 5 s = 0.8 h, the surface temperature of glass wool – with the manufacturer-specified thermal conductivity value ($\lambda = 0.027\ \mathrm{W\cdot(m\cdot K)^{-1}}$) – differs by only 0.8% from the simulated value, which falls within the experimental measurement uncertainty. A series of approximately 60 numerical experiments with randomly distributed material sections (maintaining a 20/80% binder-to-reed proportion, Fig. 3), along with extensive simulations incorporating variable thermal conductivity values for the reed component, revealed a link between the effective thermal conductivity of the composite and the manufacturing conditions. In particular, the penetration depth of the biopolymer adhesive into the porous reed structure – governed by temperature and pressure during pressing – was found to significantly affect the resulting material properties. Additionally, the degree of reed fragmentation and the effectiveness of void filling between coarse particles were shown to have a measurable influence on the overall thermal performance.

Conclusions

1. The developed insulation material, composed of chopped bulrush and carrageenan binder, demonstrated the thermal insulation performance reaching up to 98% of the efficiency of conventional glass wool, based on controlled laboratory tests in both heating and cooling cycles.

2. The inclusion of approximately 30% fine particles (1-5 mm) effectively reduced internal air voids, contributing to increased packing density and reduced thermal conductivity.
3. Numerical simulations of heat transfer across heterogeneous materials closely aligned with experimental results, supporting the validity of the model in predicting thermal behaviour of plant-based composites.
4. The results confirm that it is feasible to produce high-performance insulation materials from locally available aquatic plants and biodegradable binders, offering a sustainable alternative to synthetic insulation.
5. Further optimization of particle distribution and moisture sensitivity is recommended for improving long-term durability under variable environmental conditions.

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Author contributions

Conceptualization, U.Ž.; methodology, U.Ž. and D. Ļ.; software, U. Ž.; validation, U. Ž. and D. Ļ; formal analysis, U. Ž. and D. Ļ..; investigation, U. Ž.; data curation U. Ž.; writing – original draft preparation, U. Ž. and D. Ļ.; writing – review and editing, U. Ž. and D. Ļ.; visualization, U. Ž.; project administration, U. Ž.; funding acquisition, U. Ž. All authors have read and agreed to the published version of the manuscript.

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