CARRAGEENAN AS BINDER FOR THERMAL INSULATION MATERIALS DERIVED FROM FRESHWATER PLANTS

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Abstract. The growing demand for sustainable and biodegradable materials has led to increased interest in bio-based thermal insulation materials. In this study, carrageenan is investigated as a natural binder for producing thermal insulation materials from freshwater plants, specifically common reed (*Phragmites australis*) and lake bulrush (*Scirpus lacustris*). The binding performance of carrageenan in combination with these plant fibres is crucial for determining the mechanical and thermal stability of the final material. The research focuses on the interaction between carrageenan and the plant surface, evaluating the contact angle, adhesion strength, and durability of the binder. These properties directly influence the cohesion and mechanical integrity of the insulation material. The adhesion characteristics were analysed through experimental testing, highlighting the role of carrageenan in ensuring a stable and uniform composite structure. One of the key challenges in utilizing carrageenan is its hydrophilic nature, which may affect the long-term stability and moisture resistance of the insulation material. To address this challenge, surfactants were incorporated as additives to modify the surface properties and improve the hydrophilic characteristics. The influence of these surface-active agents on carrageenan adhesion and water resistance was assessed to enhance the overall performance of the insulation material. This study provides valuable insights into the potential application of carrageenan as a sustainable binder for bio-based insulation materials. By optimizing adhesion properties and hydrophilicity, this approach contributes to the development of environmentally friendly insulation solutions with improved durability and mechanical performance. The results support the viability of plant-based insulation materials as an alternative to synthetic counterparts, advancing the field of sustainable construction materials.

Keywords: carrageenan, thermal insulation, freshwater plants, surfactants, sustainable materials.

Introduction

The increasing awareness of environmental challenges and the urgent need for sustainable solutions have driven significant interest in the development of eco-friendly materials for the construction industry. Among these, bio-based thermal insulation materials offer a promising alternative to conventional synthetic insulators, which are often non-biodegradable, energy-intensive to produce, and environmentally harmful at the end of their life cycle.

Natural plant fibres, particularly those sourced from renewable and widely available freshwater plants, such as common reed (*Phragmites australis*) and lake bulrush (*Scirpus lacustris*), have emerged as attractive raw materials for insulation applications due to their low density, good thermal properties, and biodegradability. However, the production of effective fibre-based insulation materials relies heavily on the choice of a suitable binder that can ensure mechanical integrity, cohesion, and durability under varying environmental conditions.

Carrageenan, a polysaccharide derived from the Baltic Sea red seaweed (*Furcellaria lumbricalis*), is a natural, biodegradable polymer [1] known for its gel-forming capabilities and film-forming properties. Its potential as a binder for plant-based insulation composites is of particular interest due to its availability and compatibility with natural fibres. Nonetheless, its hydrophilic nature poses a significant challenge, particularly in applications requiring long-term moisture resistance and structural stability.

This study investigates the application of carrageenan as a natural binder in thermal insulation materials derived from freshwater plant fibres. It focuses on the binder–fibre interactions, analysing contact angles, adhesion strength, and the durability of the composite material. Furthermore, the study explores the role of surfactants as additives to modify carrageenan’s surface characteristics, aiming to reduce hydrophilicity and improve water resistance without compromising bonding performance.

Materials and methods

A. Carrageenan as a Natural Binder

The demand for sustainable insulation solutions has led to increased research into plant-based materials due to their biodegradability, renewability, and low environmental footprint [2]. Freshwater

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plants such as *Phragmites australis* (common reed) and *Scirpus lacustris* (lake bulrush) are abundant, fast-growing, and have favourable thermal insulation properties, making them viable candidates for composite insulation panels. Previous studies have demonstrated that lignocellulosic fibres possess good thermal resistance and can be integrated into insulation boards with minimal environmental impact.

Binders play a crucial role in ensuring the cohesion, mechanical stability, and durability of fibre-based composites. Traditional synthetic binders, such as polyurethane or phenol-formaldehyde resins, provide strong adhesion but are associated with toxicity, non-renewability, and poor biodegradability. Natural binders like starch, lignin, and alginate have been investigated as more environmentally friendly alternatives. However, their performance often depends on compatibility with the plant fibres and resistance to moisture.

Carrageenan, derived from seaweed, has already been studied in combinations with other bio-based materials [3]. Carrageenan is a sulphated polysaccharide extracted from red algae *Furcellaria lumbricalis*, widely used in the food, pharmaceutical, and cosmetic industries for its gelling, thickening, and stabilizing properties. Its potential as a binder in fibre composites has gained attention due to its ability to form films and its non-toxic, biodegradable nature. Carrageenan can create uniform gels that can encapsulate fibres, potentially enhancing interfacial bonding. However, its hydrophilic behaviour presents a limitation in applications where water resistance and dimensional stability are critical.

To overcome carrageenan moisture sensitivity, surface modification strategies have been explored. Surfactants, which lower surface tension and modify interfacial interactions, can be used to improve the adhesion properties of hydrophilic polymers [4]. Non-ionic and amphiphilic surfactants have shown promise in enhancing water repellence while preserving mechanical integrity. Prior research indicates that the right choice and concentration of surfactants can significantly alter wettability, the contact angle, and ultimately the long-term performance of natural fibre composites.

While carrageenan has been studied in biomedical and packaging applications, its use as a binder in insulation materials made from freshwater plants remains largely unexplored. Moreover, limited information is available on how surfactant-treated carrageenan affects fibre adhesion and moisture resistance. This research addresses these gaps by evaluating carrageenan’s performance in freshwater plant composites and examining the effectiveness of surfactants in optimizing the composite’s physical and mechanical properties.

B. Role of Potassium Ions in Surfactant Activity and Surface Modification

One way to increase the water resistance of the carrageenan-aquaculture combination is to add potassium ions. Potassium ions (K^+) themselves are not surfactants; however, they play a pivotal role in modifying the surface properties of biopolymer systems, notably κ-carrageenan. This sulphated polysaccharide, extracted from red seaweed, exhibits unique gelling properties in the presence of specific cations. The interaction between K^+ ions and κ-carrageenan is crucial for gel formation. K^+ ions facilitate the transition of κ-carrageenan chains into a helical structure, promoting aggregation into a three-dimensional network. This network enhances the gel mechanical strength and stability. Studies have shown that increasing potassium salt concentration leads to more rigid κ-carrageenan gels, while decreasing rupture strain. Additionally, crosslinking κ-carrageenan hydrogels with KCl has been demonstrated to significantly increase compressive strength and provide excellent water retention capacity [5]. Beyond mechanical reinforcement, K^+ ions contribute to the water resistance of κ-carrageenan-based materials. The ionic crosslinking induced by K^+ reduces the hydrophilicity of the polymer matrix, thereby decreasing water uptake. This property is particularly beneficial in applications requiring moisture-resistant materials. For instance, κ-carrageenan composite films, when modified with cationic surfactants, exhibit enhanced mechanical strength and water resistance, making them suitable for water-induced applications [6].

While K^+ ions alone are not surfactants, their presence can influence the behaviour of surfactant molecules within the biopolymer system. Incorporating surfactants such as sorbitan monolaurate into κ-carrageenan gels affects the rheological properties, leading to variations in viscosity and shear stress. This interaction suggests that K^+ ions can modulate the effectiveness of surfactants in altering the surface characteristics of κ-carrageenan-based materials [7].

The gelation of κ-carrageenan is primarily driven by the presence of specific cations, with K^+ being particularly effective. These ions interact with the negatively charged sulphate groups on the carrageenan chains, facilitating the formation of double helices and their subsequent aggregation into a three-dimensional network. This network formation is essential for developing strong, thermally stable gels with reduced water solubility. The stabilization of junction zones by K^+ ions enhance the gel structural integrity and decreases its affinity for water, thereby improving water resistance [8].

The type of the cation present significantly influences the properties of κ-carrageenan gels. Studies have demonstrated that K^+ ions are more effective than sodium ions (Na^+) in promoting gelation. K^+ ions lead to the formation of stronger and more rigid gels, whereas Na^+ ions result in weaker gel structures. This difference is attributed to the specific binding affinity of K^+ ions to the carrageenan helices, which facilitates tighter junction zones and enhances the material overall water resistance [2; 4].

The incorporation of K^+ ions into κ-carrageenan hydrogels has practical applications in improving their mechanical strength and durability. For instance, crosslinking κ-carrageenan with potassium chloride (KCl) has been shown to significantly increase compressive strength and reduce degradation rates. Hydrogels crosslinked with KCl exhibited enhanced water retention and maintained structural integrity over extended periods, highlighting the role of K^+ ions in augmenting water resistance and mechanical robustness [5].

Results and discussion

During the development of renewable biodegradable thermal insulation from aquaculture, the basic materials were obtained – lake reeds and bulrushes. After drying to 10-12% residual moisture, the materials (Fig. 1 and 2) were crushed into fixed 3-4 cm long pieces. Their porous structure, supplemented by a chaotic arrangement, provides great advantages in fixing air pockets, which is an important prerequisite for the development of effective thermal insulation. In addition, about a third of the total mass of rushes was crushed more finely to 0.1-0.5 cm to achieve an almost powdery consistency. These fine particles are excellent for filling the gaps between larger pieces.

Fig. 1. **Sample of crushed common reed (*Phragmites australis*). 3-4 cm long fibres dominate, with powdery filling**

Fig. 2. **Sample of chopped lake rush (*Scirpus lacustris*). The main mass consists of 1.5-3 cm long fibres, between which a finer filling can be observed**

The fine particles, with their large surface area, attract carrageenan, derived from seaweed, which serves as a binding agent. At about 30% of the presence of fine reed particles, the gaps between the thickest pieces of bulrush are well filled. In contrast, well-dried reeds crumble in the direction of the fibres, which leads to the formation of thin, elongated fibres. These fibres with high mechanical strength in the longitudinal direction form a strong reinforcement in the total volume of the product. Since the arrangement is random, the spatial reinforcement perfectly holds the total thermal insulation mass in one formation (Fig. 3).

To bond the processed reed and rush materials, experiments were conducted with a pure carrageenan binder, then 50% potato starch was added to which potassium chloride KCl at a concentration of 0.1 M/l was added to increase water resistance. All subsequent results refer to the full binder composition with carrageenan, starch and potassium chloride. The addition of additives is also noted by other authors [9-11] whose works have studied the gelation mechanism of carrageenan and the water-repelling properties of potassium ions.

After dissolving in water and heating, the resulting binder mixture was used in a ratio of 1:6 (carrageenan and starch relative to reeds) by mass of DOM. Technological operations include mixing, pressing, filling into moulds, drying at a temperature of 40 °C, and ventilation.

Fig. 3. **Sample of the developed thermal insulation, size 20 x 20 x 5 cm. One-piece structure, reinforced with longer reed fibres**

Fig. 4. **Close-up view. Reed fibres arranged in random directions between pieces of bulrushes**

In the close-up (Fig. 4), a mixture of rushes and reeds can be observed. The reinforcing reed fibres are arranged in random directions and form a single-piece structure throughout the volume of the thermal insulation material. In industrial applications, using a rotating mixer and pouring the mass into a mold will result in a smooth material with a uniform distribution of fine/large particles.

Fig. 5. **Fine particles of reeds and rushes on the background of large pieces. Optical microphotography, magnification 20x**

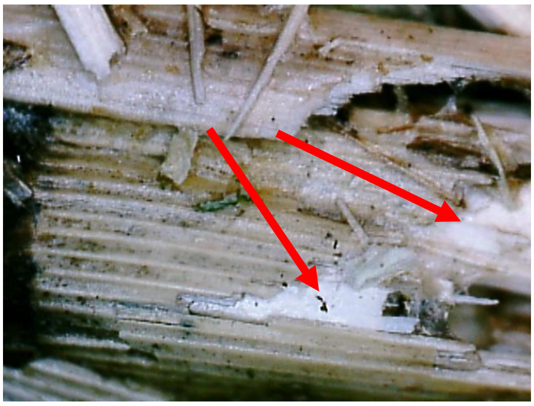

Fig. 6. **Carrageenan layer on a piece of reed. Thicker deposits are marked with arrows. Optical micrograph, magnification 20x**

A closer look shows good adhesion of carrageenan to fine and coarse reed and bulrush particles. Optical microscope images (Fig. 5 and 6) show that carrageenan has high hydrophilic properties on the surface of dried aquacultures, and carrageenan does not crack or separate after drying. This effect was achieved by adding glycerol $C_3H_8O_3$ to the carrageenan solution during the preparation process in a ratio of 1:10 by volume.

Good adhesion of carrageenan is confirmed by the mechanical properties of the developed thermal insulation material. Tensile tests were performed on a 3 cm wide, 12 cm long and 2 cm thick material sample, stretching it and measuring the tensile force. The test results are summarized in Table 1. A large difference in tensile forces is visible compared to the biocomposite from carrageenan and wheat straw [3], where the material was finely chopped, and no longer fibres were left for reinforcement. The standard deviation from these five measurements is 7.9 kPa, or approximately 8%, which provides a good estimate of the strength level of the developed composite.

Table 1

Tensile tests of samples

Sample No.	Applied force, N	Calculated force per cross-sectional area, kPa
1	57.447	95.745
2	52.302	87.170
3	66.129	110.215
4	62.334	103.890
5	59.594	99.323
Average	**59.561**	**99.268**

Water droplet contact angle measurements show moderate hydrophilic properties of the surface of the developed thermal insulation material coated with carrageenan with added starch and potassium K^+ ions. However, a significant increase in the contact angle of a water droplet on the surface of the biocomposite with added starch and potassium chloride KCl is observed. Fig. 7 shows the contact angle for a clean, uncoated bulrush surface, Fig. 8 shows an increased contact angle for a surface coated with a carrageenan + starch + potassium chloride binder.

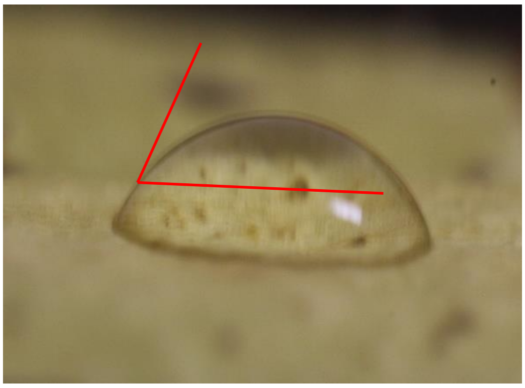

Fig. 7. **Drop of water on the surface of uncoated natural reeds. Contact angle (79 ± 2)°, measured manually**

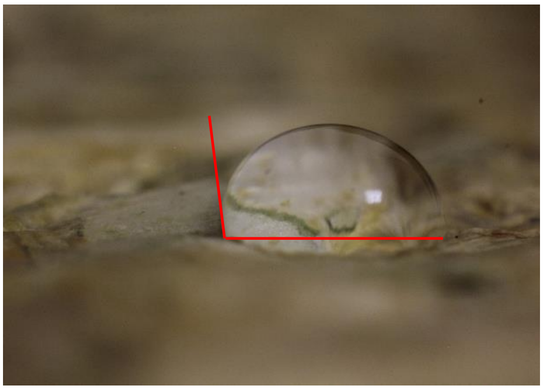

Fig. 8. **Drop of water on the surface of rush coated with a binder of carrageenan, starch and potassium chloride. Contact angle (98 ± 2)°**

The experimental results confirmed that carrageenan, when combined with starch and potassium chloride, forms a cohesive and mechanically stable structure suitable for thermal insulation applications. The inclusion of longer reed fibres significantly improved tensile strength due to spatial reinforcement, which is not observed in purely powdered biocomposites. Potassium ions enhanced carrageenan gelation and reduced hydrophilicity, as evidenced by the increase in water contact angle from 79° to 98°, indicating improved moisture resistance. This aligns with previous studies highlighting the role of K^+ in promoting strong helix aggregation and reducing water uptake in κ-carrageenan systems. Overall, the synergistic effect of biopolymer crosslinking, surfactant action, and fibre architecture demonstrates the potential of carrageenan-based materials for sustainable insulation products.

Comparative thermal performance testing was conducted between the developed reed-based biocomposite insulation and conventional industrial glass wool to evaluate the effectiveness of the natural material under controlled conditions. The experimental setup ensured identical boundary conditions for both samples, including equivalent heating sources and sample dimensions. The dimensions of the samples corresponded to those shown in Fig. 3, ensuring comparable thermal paths and heat flow areas for accurate evaluation. During dynamic heating and cooling cycles, a greater thermal inertia was observed for the reed-based composite, likely due to its higher volumetric heat capacity compared to glass wool. However, under quasi-static conditions, the heat retention capacity – i.e. the ability to maintain a stable interior temperature – proved to be more critical, and the reed composite exhibited strong performance in this regard. As illustrated in Fig. 9, the thermal efficiency of the reed insulation material reached between 87% and 89% of that achieved by glass wool. This result highlights the promising capability of the freshwater plant-based composite to closely match the performance of well-established synthetic insulation materials, despite differences in composition and internal structure.

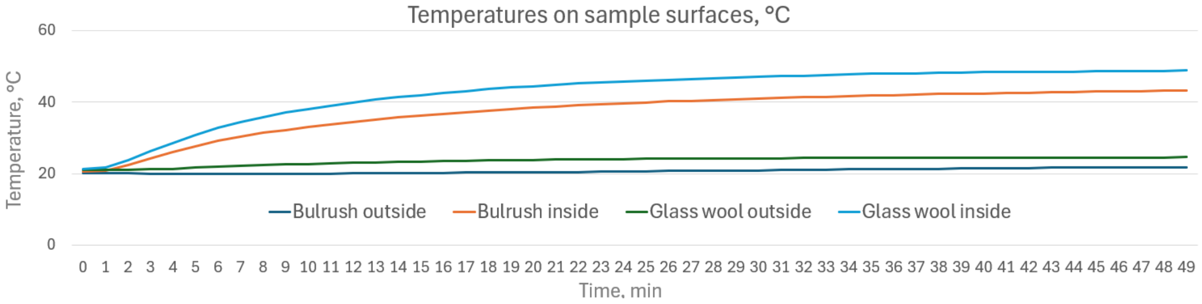

Fig. 9. **Comparative thermal insulation efficiency of the developed reed-based composite versus industrial glass wool under identical heating conditions**

Further insight into the thermal performance was gained by analysing the temperature differences between the interior and exterior surfaces of the samples, as shown in Fig. 10. Throughout the measurement period, the reed-based material exhibited slightly larger temperature gradients compared to glass wool, but the difference remained within a relatively narrow range. This behaviour indicates that although the natural composite has marginally higher thermal conductivity, it still provides substantial resistance to heat flow, maintaining the interior temperature close to that achieved by glass wool.

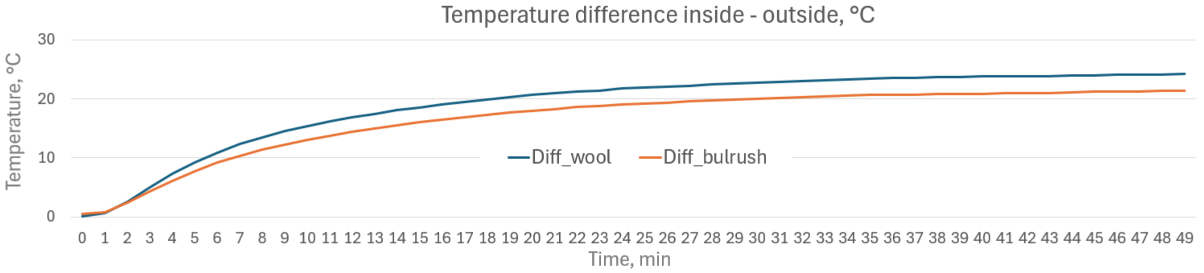

Fig. 10. **Temperature difference profiles between the internal and external surfaces of the developed reed composite and glass wool during thermal testing**

The observed thermal efficiency levels (87–89%) suggest that with further optimization of material composition – such as fibre orientation, particle size distribution, and binder penetration depth – the reed-based composite could potentially bridge the remaining performance gap. Additionally, the biocomposite offers significant sustainability advantages, including biodegradability and the use of renewable resources, further strengthening its attractiveness for eco-friendly construction applications.

Conclusions

1. Carrageenan proved to be an effective natural binder for freshwater plant-based thermal insulation materials, forming a uniform and cohesive composite structure with good mechanical integrity.
2. The addition of potassium chloride (KCl) significantly enhanced the water resistance of the insulation material by reducing the hydrophilicity of the carrageenan matrix and increasing the water droplet contact angle from 79° to 98°.
3. Incorporating fine and coarse plant particles with randomly oriented long reed fibres provided internal reinforcement, improving tensile strength and structural stability across the entire volume of the composite.
4. The combination of carrageenan with starch and potassium ions produced a stable and mouldable composite mass, suitable for shaping into panels with even distribution of material and fibre reinforcement.
5. The developed biocomposite offers a promising alternative to synthetic insulation materials, contributing to the advancement of sustainable, biodegradable solutions in the construction industry.

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