HYDROGEL AS A HYGROSCOPIC MATERIAL IN ARCHITECTURE: POTENTIAL FOR SUSTAINABLE CONSTRUCTION AND IMPROVEMENT OF COMFORT IN THE BUILDING

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ABSTRACT

Hygroscopicity is a natural phenomenon of attracting and retaining water molecules by absorption from the environment. Thus, there are materials that have this characteristic and can absorb and retain, but also control moisture from the environment. This paper will explore the application of such materials in construction, i.e. sustainable construction, focusing on the environment and the role of the materials themselves in creating sustainable urban spaces. Hygroscopic materials have the ability to passively influence the microclimate of buildings by absorbing moisture during periods of high humidity, or conversely, by releasing moisture in dry conditions. In this way, hygroscopic materials contribute to improving thermal regulation and reducing the need for mechanical heating and cooling systems in spaces. In addition to saving energy, their use can also help mitigate the urban heat island effect and improve indoor air quality.

The paper will specifically address the use of hydrogel components as materials with hygroscopic properties in building facades and certain building segments through two case studies with the aim of understanding the functioning of these components as segments of the building envelope in terms of energy efficiency and comfort of living in such a space.

The aim of the research is to open up new possibilities for the application of these materials, which, among other things, relate to the formation of objects that have the ability to dynamically change and adapt to different environmental conditions similar to hygroscopic materials. It is clear that hygroscopic materials have great potential in the context of improving sustainable urban development. The result of the research at the very end is that such materials significantly improve the thermo-energy properties and energy efficiency of the building itself.

KEYWORDS _ *Hygroscopicity, Sustainability, Technology in architecture, Hydrogel, Microclimate regulation*

INTRODUCTION

Microclimate regulation in construction facilities is a key factor in achieving energy efficiency and improving user comfort. Hygroscopic materials, capable of absorbing and releasing moisture from the environment, have been used for centuries in traditional architecture, where natural materials such as wood or clay served as passive regulators of the indoor climate (Szturcová and Šťastná, 2022). Contemporary research, however, opens up possibilities for improving these principles through the application of innovative materials such as hydrogel, which have improved hygroscopic characteristics and can be integrated into the facade systems of modern buildings (Zhou et al., 2021). Hydrogel is a material consisting of two phases - a porous and permeable solid structure, and a liquid (at least 10%), such as water or some other liquid. Hydrogel, or its solid phase, cannot dissolve in water, but it has the ability to absorb considerable amounts of water or biological fluids (Wikipedia, n.d.). The integration of hydrogel into building elements, especially facade systems, enables the creation of dynamic and adaptive architectural solutions that contribute to energy efficiency and sustainability. One of the researches that will be discussed in more detail in this paper through a case study showed that hydrogel components in facade elements can significantly reduce the temperature of interior spaces and reduce the need for mechanical cooling systems. This paper explores the possibilities of applying hydrogel in facade systems through the analysis of two case studies. The first example examines the use of hydrogels and ceramics in passive cooling facade systems (Stott, 2015), while the second focuses on the application of hydrogel-glass in windows to improve energy efficiency (Fu et al., 2022). The goal of the research is to look at the potential of hygroscopic materials, in this case hydrogel, in the context of improving sustainable architecture.

Research methodology

The methodological approach of this paper is based on a qualitative analysis of secondary sources and case studies that demonstrate the application of hydrogel in modern facade systems (Figure 1). The research was conducted through the analysis of two representative examples - a passive cooling system based on hydrogel and ceramics, and an example of hydrogel-glass as a window element. Through the analysis of both systems, the work examines how the hygroscopic properties of hydrogel contribute to the regulation of the internal microclimate and the energy efficiency of buildings. In addition, relevant scientific papers, experimental data and simulation results were used to explore the possibilities of further integration of these materials into sustainable architectural practice.

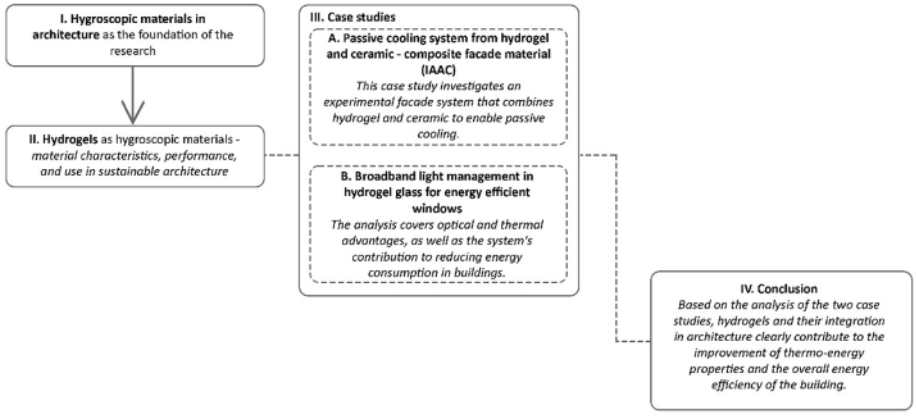


Figure 1: Research Process Diagram (authors illustration)

HYDROGEL - HYGROSCOPIC MATERIAL

Hydrogel is a type of hygroscopic and polymeric materials with the ability to absorb and retain significant amounts of water, which makes it extremely useful in architecture, especially in situations related to moisture regulation. The network structure of this material enables reversible absorption and release of water, which opens up new possibilities for the development of smart systems that can improve the energy performance of buildings (Ahmed, 2015). Hydrogel is also characterized by its high hydrophilicity, ability to swell in water environments and resistance to degradation in different atmospheric conditions. In addition, it is thermally stable and easily adapts to different environmental parameters, all of which prove that this material is suitable for various architectural applications. Studies have shown that hydrogel can significantly contribute to the internal microclimate of buildings, enabling passive cooling and increasing comfort without energy costs (Lai and Lin, 2024).

Mechanisms of moisture absorption and release

The moisture absorption process of a hydrogel is based on its molecular structure, where hydrophilic groups attract water molecules from the environment. This mechanism stimulates dynamic humidity control in closed spaces. In periods of high humidity, the hydrogel absorbs moisture, while in dry conditions it is released, which naturally regulates the microclimate (Zhou, Zhang & Wang, 2021).

Advantages of hydrogel compared to other hygroscopic materials

Unlike traditional hygroscopic materials such as wood and clay, hydrogels have a higher absorption capacity and a faster reaction to changes in humidity in the environment. Additionally, their transparency and adaptability could potentially be an advantage in terms of integrating them into facade systems without significant impact on the aesthetics of the building. The use of hydrogel glass in windows, for example, can significantly improve thermal control and reduce the need for air conditioning within the building itself (Fu et al., 2022).

STUDY CASE ANALYSIS

Research on the effects of hygroscopic materials in architectural envelopes is supported by the analysis of two different case studies, which through an experimental and innovative approach show how hydrogel as a hygroscopic material can directly affect the energy efficiency and microclimate of buildings. Hydrogel is able to absorb water when the air around is heated to vaporization and then cools the room up to 5°C. The mechanism is inspired by the way the human body cools (Institute for Advanced Architecture of Catalonia, 2014).

First Case Study: Passive Cooling System with Hydrogel-Ceramic Composite at IAAC

The first study, developed within the research center IAAC (Institute for Advanced Architecture of Catalonia), deals with the development of a passive cooling system based on a combination of hydrogel and ceramics. The system works on the principle of water absorption and evaporation, using the hydrogel's ability to absorb moisture from the atmosphere and gradually release it in the form of steam cools (Institute for Advanced Architecture of Catalonia, 2014). This process not only lowers the temperature in the environment, but also allows maintaining a pleasant internal microclimate without the need for mechanical devices. It is particularly significant that the prototype was tested in the real climatic conditions of Barcelona, thus confirming its effectiveness in urban, warm environments. At the same time, the ceramic structure itself contributes to the capillary distribution of water and enables uniform evaporation, while the hydrogel acts as an active hygroscopic component (Figure 3).

This study shows how a combination of traditional and modern materials can lead to a functional and sustainable solution to overheating problems in urban areas (Stott, 2015).

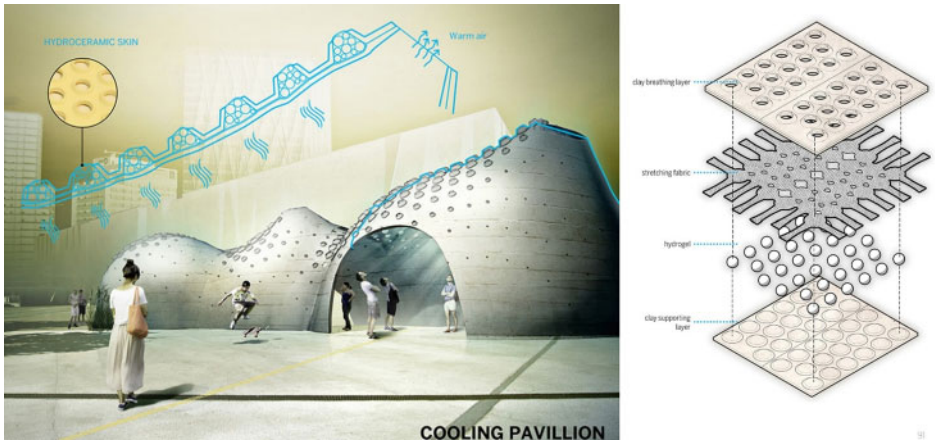


Figure 2: Passive cooling mechanism in pavilion with hydroceramic skin (left) and hydrogel panel appearance (right)

Second Case Study: Hydrogel-Glass as an Energy-Efficient Window Element with Broadband Light and Heat Management

The second case study is focused on the application of hydrogel-glass as a window element with broadband light and heat management properties. Research has shown that this type of window, which consists of a layer of hydrogel applied to the glass, allows for better transmission of the visible spectrum of light, blocking of near-infrared radiation and increased emission in the mid-infrared range (Figure 4). Such a combination of properties results in a reduction in the need for artificial lighting and space cooling, which directly affects energy savings. The results of simulations, carried out for typical school buildings in several climate zones, show savings in the range of 2.37 to 10.45 MJ/m² per year. In addition to laboratory tests, the study also includes measurements in house models, where in a real environment it was shown that the temperature of the interior with hydrogel-glass is up to 3.5°C lower compared to standard glass (Fu et al., 2022).

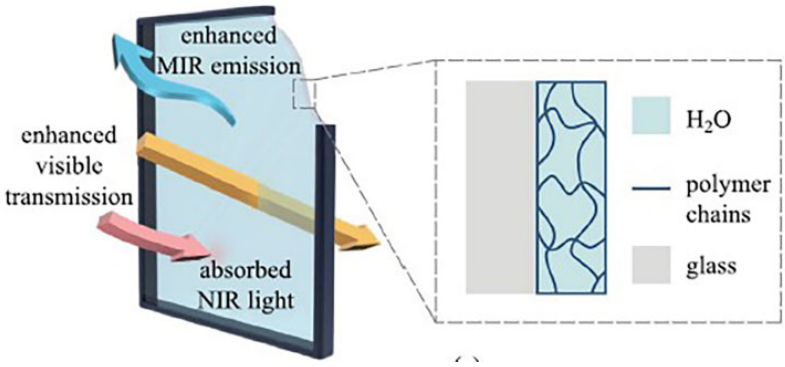


Figure 3: Structure design and working principle of the hydrogel-glass

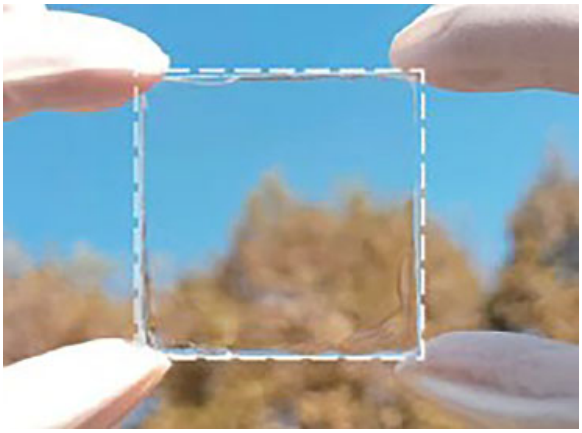


Figure 4: Photograph of the fabricated hydrogel-glass

The comparative analysis of these two studies indicates the diversity of approaches in the application of hygroscopic materials, specifically hydrogel, but also its universal value in the context of energy efficiency and microclimate stability. While the first study explores a bio-inspired, material-structural response to climate challenges, the second demonstrates the potential of integrating hygroscopic technologies into standard building elements, such as windows. The common denominator of both analyzes is the use of natural material properties in order to reduce the need for energy and improve the quality of the interior space, which indicates a clear direction in the development of sustainable architecture.

CONCLUSIONS

The research of hygroscopic materials, with a special focus on hydrogels, reveals a significant potential for improving the energy efficiency of buildings and creating more adaptable, environmentally friendly architectural solutions. The analyzed case studies showed that such materials - hydrogel, when thoughtfully integrated into the structure of the building - either as facade components or as window elements - can have a direct impact on the microclimate, living comfort and energy consumption. However, the application of hygroscopic materials is still in the initial stage when it comes to their widespread use in architectural practice. One of the challenges is the need for greater resistance and durability in different climatic conditions, as well as the adaptation of production technologies to architectural and construction standards. In addition, there is a lack of clear normative frameworks that would enable their application to a larger number of facilities.In the coming period, research should be directed towards improving the properties of hydrogels themselves - both in terms of absorption capacity and moisture release control, and in terms of integration with other materials such as glass, concrete or biocomposites. Also, the development of intelligent systems that would enable the monitoring and management of changes in the hygroscopic behavior of materials could significantly contribute to their wider use. The potential of hydrogels lies in their ability to act as active components of the architectural “skin” - a building envelope that not only protects, but also responds, adapts and improves the quality of the interior space. This is precisely where the key to the future of sustainable architecture lies - in materials that do not imitate nature, but become an active part of it. In this context, hygroscopic materials represent an important step towards a more dynamic, efficient and environmentally conscious space.

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