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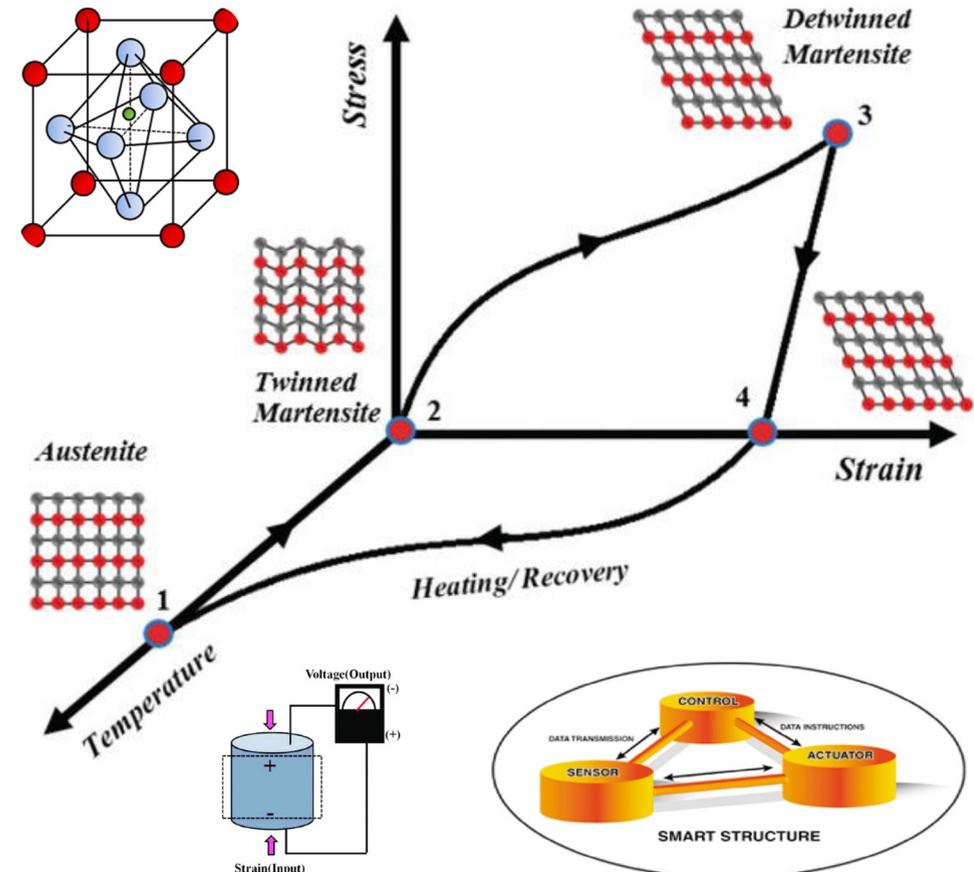
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ADVANCED APPLICATIONS AND PROPERTIES OF HYDROCERAMICS

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Abstract

Hydroceramics represent a groundbreaking advancement in the field of materials science, synergizing the strength and stability of traditional ceramics with the adaptive hydrophilic properties of modern composites. This chapter provides a comprehensive analysis of hydroceramics, detailing the innovative synthesis processes, unique physicochemical properties, and a spectrum of applications that demonstrate their transformative potential. From the meticulous design of their molecular architecture to the integration into sustainable construction, hydroceramics stand as a testament to interdisciplinary innovation aimed at meeting today's challenges in sustainability, energy efficiency, and biocompatibility. The synthesis techniques such as sol-gel processes, direct sintering, polymer-induced phase separation, and additive manufacturing are examined for their roles in shaping the functionality of hydroceramics. The chapter navigates through their diverse applications, including sustainable construction, water purification, and biomedical engineering, emphasizing their significance in both current practices and future developments. Through this exploration, the chapter sheds light on the promising future and the challenges that hydroceramics face in their journey from conceptual material to a cornerstone of sustainable technology.

Introduction

Hydroceramics emerge as a transformative class within the material sciences, ingeniously melding the inherent robustness and structural resilience of traditional ceramics with the responsive properties of hydrophilic components. This interdisciplinary synthesis not only broadens the scope of ceramic materials' applications but also introduces novel functionalities that can adapt to environmental stimuli. The genesis of hydroceramics marks a significant stride towards engineering advanced materials capable of addressing contemporary challenges in sustainability, energy efficiency, and biocompatibility. This chapter endeavours to dissect the multifaceted aspects of hydroceramics—from their nuanced synthesis pathways and distinctive physicochemical properties to their burgeoning applications and the vistas they open for future research. A meticulous examination of the molecular architecture and compositional strategies that confer hydroceramics their characteristic hydrophilicity will lay the groundwork for understanding their diverse capabilities and limitations.

At the heart of hydroceramics' unique capabilities is their hybrid molecular structure, which incorporates hydrophilic moieties into a ceramic matrix. This integration is not merely superficial or additive; it involves a covalent bonding framework that ensures the stability of the hydrophilic groups within the ceramic host, thereby imparting a durable water-attracting feature to the material. Typically, the base ceramic matrix comprises silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), or a combination thereof, known for their exceptional mechanical strength and thermal stability. The hydrophilic functionality is introduced through the integration of metal-organic frameworks (MOFs) or silica-based networks modified with polyethylene glycol (PEG) chains or other hydrophilic polymers. The precise engineering of these composite structures at the molecular level allows for the fine-tuning of the material's porosity, surface area, and water absorption capabilities, which are crucial for its intended applications.

The synthesis of hydroceramics employs advanced fabrication techniques that enable the precise manipulation of their microstructure and composition. Sol-gel processes, renowned for their versatility in producing ceramic and glass materials, play a pivotal role in hydroceramic production. This method allows for the incorporation of organic hydrophilic precursors into the sol, which later transforms into a gel, embedding the hydrophilic components within the ceramic matrix. Additionally, controlled sintering under specific temperature and atmospheric conditions can adjust the material's porosity, a critical factor in determining its water retention and transport properties. Innovations in additive manufacturing, or 3D printing, have further expanded the possibilities for creating complex hydroceramic structures with tailored porosity and surface geometries, opening new avenues for application-specific designs.

Hydroceramics are characterized by a suite of remarkable properties that distinguish them from traditional ceramics and other materials. Their hydrophilicity, a result of the embedded hydrophilic groups, endows them with unique moisture-absorbing and -releasing capabilities, essential for applications in humidity control and water harvesting. Furthermore, the engineered porosity of hydroceramics can be optimized to enhance these properties, allowing for the development of highly efficient, passive cooling systems in construction materials or for water purification and capture in arid environments. Mechanical strength, thermal stability, and chemical inertness, hallmarks of ceramic materials, are preserved in hydroceramics, making them suitable for structurally demanding applications.

The application spectrum of hydroceramics spans several key industries, each benefiting from the material's distinct properties. In the construction sector, hydroceramic panels are being explored for their potential to regulate indoor humidity and temperature passively, contributing to energy-efficient building designs. In the field of water treatment and environmental remediation, their high surface area and tunable porosity make them excellent candidates for capturing pollutants and harvesting water from the atmosphere. The biocompatible and bioactive properties of certain hydroceramic formulations also offer promising avenues in drug delivery systems and as scaffolds for tissue engineering, highlighting their potential in biomedical applications.

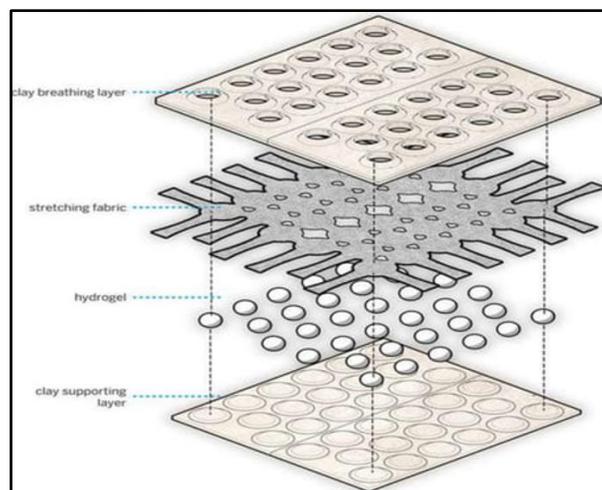


Figure 1: Exploded View of a Hydroceramic Panel

Synthesis of Hydroceramics

The fabrication of hydroceramics involves a sophisticated orchestration of chemical and physical processes, tailored to imbue the final material with its distinctive hydrophilic and structural characteristics. This section delves into the nuanced methodologies employed in the synthesis of hydroceramics, highlighting the critical parameters that influence their morphology, porosity, and functional performance. Understanding these synthesis routes is pivotal for furthering the development of hydroceramics with enhanced properties and functionalities.

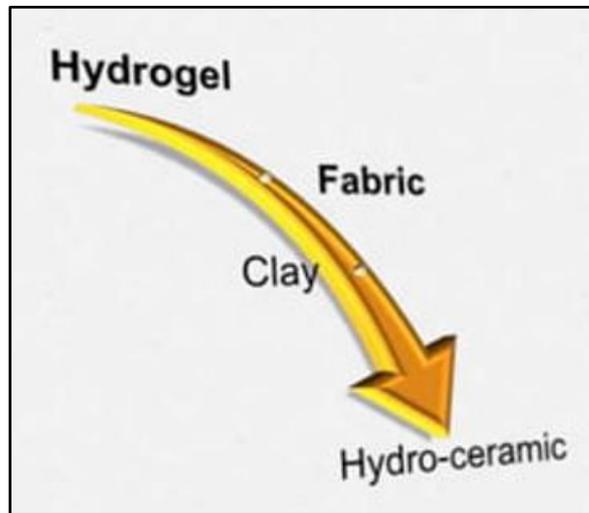


Figure 2: Hydroceramic Composition

Sol-Gel Process

The sol-gel process stands as a cornerstone in the synthesis of hydroceramics, offering unparalleled control over the material's microstructure. This method involves the transition of a colloidal solution (sol) into a gel-like network (gel), encapsulating the hydrophilic components within the ceramic matrix. Key to this process is the selection of precursors, typically silicon and aluminum alkoxides, which undergo hydrolysis and condensation reactions to form the ceramic framework. The incorporation of hydrophilic agents, such as silane coupling agents with functional groups (e.g., -OH, -COOH), occurs concurrently, ensuring their uniform distribution throughout the material. The variables of precursor concentration, pH, and reaction temperature are meticulously managed to regulate the porosity and surface area of the resulting hydroceramic, critical factors for its water absorption efficiency.

Direct Sintering

Direct sintering involves the consolidation of powdered ceramic materials under high heat, facilitating the fusion of particles to create a dense, uniform structure. For hydroceramics, this technique is adapted to preserve the embedded hydrophilic functionalities. Adjustments in sintering temperature and duration, along with the application of controlled atmospheric conditions, are essential to prevent the decomposition of hydrophilic components. Sintering parameters are optimized to achieve a balance between mechanical strength and porosity, ensuring the material's structural integrity while maintaining its moisture handling capabilities.

Polymer-Induced Phase Separation

Polymer-induced phase separation (PIPS) is a novel approach that leverages the phase separation behaviour of polymers in sol-gel derived ceramics to engineer porosity at the nanoscale. This method introduces a polymeric phase into the ceramic precursor solution, which upon certain conditions (e.g., temperature, solvent exchange) undergoes phase separation, creating a network of pores once the polymer is removed (e.g., via thermal treatment or solvent extraction). The resulting hydroceramic inherits a highly porous structure, enhancing its surface area and enabling superior water vapor interaction dynamics.

Additive Manufacturing (3D Printing)

Additive manufacturing, or 3D printing, represents a transformative approach to the fabrication of hydroceramics, allowing for the creation of complex geometries with precise control over porosity and surface texture. Utilizing digital models, hydroceramic materials are deposited layer by layer, enabling the design of structures with tailored pore distribution and orientation. This method is particularly advantageous for producing bespoke components for specific applications, such as custom-tailored water capture devices or intricate scaffolds for tissue engineering.

Table 1: Comparative Analysis of Hydroceramic Synthesis Methods

Synthesis Method	Porosity	Mechanical Strength	Hydrophilicity	Advantages	Limitations
Sol-Gel Process	High, adjustable through process parameters	Moderate to high, depending on post-processing	High, due to uniform distribution of hydrophilic components	Precise control over microstructure; uniform incorporation of hydrophilic components	Requires careful control of process conditions; may involve complex post-processing steps
Direct Sintering	Moderate to high, adjustable by sintering conditions	High, due to dense ceramic matrix	Moderate, depends on the integration of hydrophilic phases	Excellent mechanical properties; suitable for structural applications	High temperatures may degrade hydrophilic components; limited control over microstructural porosity
Polymer-Induced Phase Separation (PIPS)	Very high, tailored through polymer choice and concentration	Moderate, influenced by resultant porosity	High, enhanced by increased surface area	Enables nanoscale porosity; high surface area ideal for water interaction	Complex process; removal of polymer phase can be challenging
Additive Manufacturing (3D Printing)	High, precisely controlled through printing parameters	Variable, dependent on material and printing precision	Moderate to high, can be enhanced by material formulation	Customizable shapes and structures with controlled porosity; rapid prototyping	Material choice may be limited; requires specialized equipment

The above table provides a snapshot of the synthesis methods available for hydroceramics, highlighting their impact on critical material properties such as porosity, mechanical strength, and hydrophilicity. Each method presents a unique set of advantages that cater to different application needs, from structural components requiring high strength to materials optimized for maximum water interaction due to their high porosity and surface area. The choice of synthesis technique thus depends on the specific requirements of the intended application, balancing factors such as mechanical integrity, moisture management capabilities, and the complexity of the manufacturing process.

Properties of Hydroceramics

The innovative integration of hydrophilic components into ceramic matrices endows hydroceramics with a unique set of properties, making them highly versatile and applicable across various domains. This section elucidates the core properties of hydroceramics, including their mechanical, thermal, chemical, and specifically hydrophilic characteristics. Understanding these properties is crucial for leveraging hydroceramics in targeted applications, from construction and environmental sustainability to healthcare and beyond.

Mechanical Properties

Hydroceramics exhibit a robust mechanical profile, characterized by high compressive strength and hardness, which are hallmark traits of conventional ceramics. These properties are primarily attributed to the dense, covalently bonded ceramic matrix. The mechanical strength of hydroceramics can be finely tuned by adjusting the porosity during the synthesis process, allowing for a strategic balance between strength and other functional properties, such as hydrophilicity and thermal conductivity.

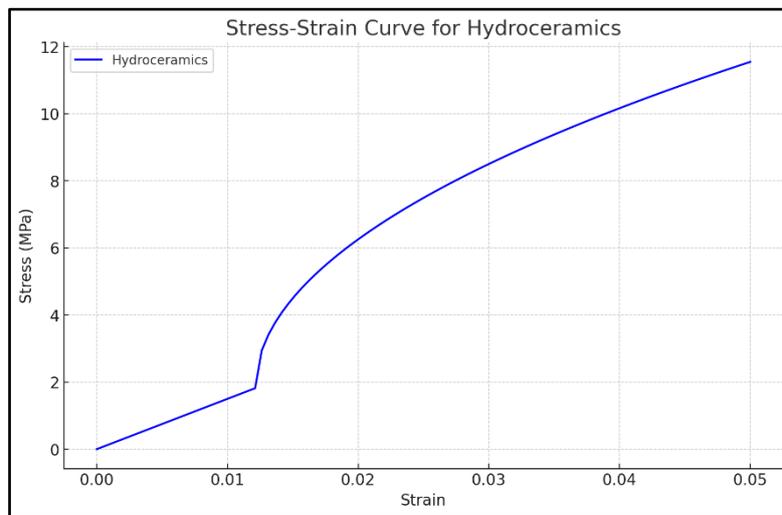


Figure 3: Stress-Strain Curve for Hydroceramics

Thermal Properties

The thermal properties of hydroceramics, including thermal conductivity and thermal stability, are significantly influenced by their porosity and the nature of the hydrophilic components integrated within the matrix. Generally, hydroceramics possess lower thermal conductivity compared to traditional ceramics, owing to their enhanced porosity. This feature makes them excellent insulators and ideal for applications requiring temperature regulation. Furthermore, hydroceramics demonstrate remarkable thermal stability, retaining their structural integrity and functionality under varying thermal conditions.

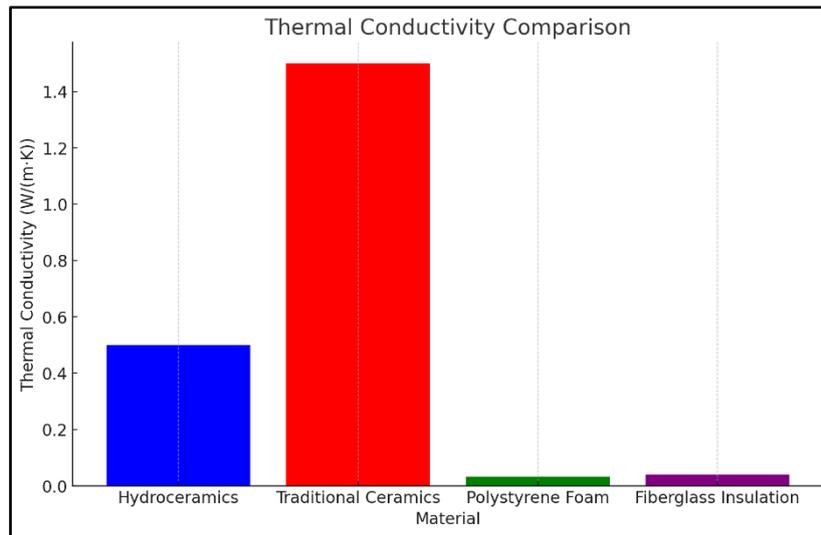


Figure 4: Thermal Conductivity of hydroceramics compared to traditional ceramics, polystyrene foam, and fiberglass insulation

The bar chart above compares the thermal conductivity of hydroceramics to that of traditional ceramics and other insulating materials, such as polystyrene foam and fiberglass insulation. Hydroceramics exhibit lower thermal conductivity than traditional ceramics, indicating better insulating properties. This characteristic makes hydroceramics suitable for applications requiring thermal insulation, where minimizing heat transfer is essential. In comparison, polystyrene foam and fiberglass insulation have significantly lower thermal conductivity values, highlighting their superior insulating abilities. However, the comparative advantage of hydroceramics lies in their structural strength and environmental resistance, combined with effective insulation capabilities, offering a balanced solution for various engineering and architectural applications.

Chemical Properties

Chemical stability in various environments is another distinguished characteristic of hydroceramics. They are resistant to corrosion, degradation, and chemical attacks, making them suitable for use in harsh environments, such as industrial chemical processes or outdoor architectural elements. The incorporation of hydrophilic components does not compromise their chemical resilience, as these are securely embedded within the ceramic matrix, protected from direct chemical exposure.

Hydrophilic Properties

The defining feature of hydroceramics is their hydrophilicity, which enables them to absorb and retain water significantly more than traditional ceramics. This property is a result of the strategic integration of hydrophilic polymers or molecules within the ceramic matrix, creating materials that can interact with water molecules effectively. The capacity for water absorption and desorption in hydroceramics can be engineered to suit specific applications, from moisture regulation in buildings to water harvesting technologies.

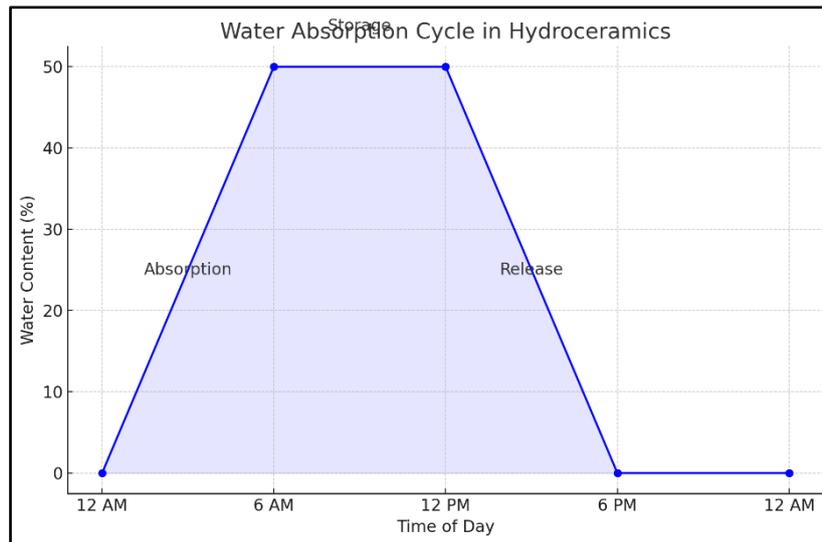


Figure 5: Water Absorption Cycle in Hydroceramics

The plot above illustrates the water absorption cycle in hydroceramics over a 24-hour period, highlighting their dynamic interaction with the environment. The cycle begins with the absorption phase in the early hours, where hydroceramics absorb moisture from the air, reaching a peak water content. This is followed by a storage phase during the day, where the water content remains relatively stable, indicating that the hydroceramics are retaining the absorbed water. As the day progresses into the evening and the ambient temperature decreases, the release phase occurs, with hydroceramics releasing the stored water back into the environment.

This cyclical behaviour demonstrates the potential of hydroceramics for applications in passive cooling systems, where the absorbed water can evaporate, reducing the ambient temperature, or in water harvesting technologies, where water from the air can be collected and used.

Environmental Interaction

Hydroceramics have a unique interaction with their environment, primarily due to their ability to absorb, store, and release water. This dynamic interaction facilitates applications such as passive cooling in buildings, where hydroceramics absorb moisture from the air during cooler periods and release it during warmer periods, reducing the need for active cooling systems. Additionally, their capacity for water absorption makes them promising candidates for environmental remediation, such as capturing water from fog in arid regions.

Applications of Hydroceramics

The distinctive properties of hydroceramics, especially their hydrophilicity, porosity, and thermal behavior, make them suitable for a wide array of applications. This section explores the practical uses of hydroceramics, underscoring their potential to address challenges in sustainable construction, water purification, biomedical devices, and more. The versatility of hydroceramics opens new horizons in material science and engineering, offering innovative solutions to longstanding problems.

Sustainable Construction

Hydroceramics have been making a significant impact in the construction industry, particularly in developing sustainable building solutions. Their ability to regulate indoor humidity and temperature naturally can lead to substantial energy savings. For instance, hydroceramic façades and roofing tiles can absorb moisture from the air on humid days and release it when conditions are drier, thus maintaining a comfortable indoor climate without the constant use of air conditioning systems. Additionally, their low thermal conductivity makes them excellent insulators, further enhancing their energy efficiency.

Water Purification and Harvesting

The high porosity and surface area of hydroceramics enable them to capture and filter water from the air, making them invaluable in water-scarce regions. These materials can be designed to condense fog or dew into liquid water, which is then collected for drinking or irrigation. Furthermore, their ability to absorb and neutralize contaminants presents a promising avenue for water purification applications, offering a passive, energy-efficient method of providing clean water.

Biomedical Applications

In the biomedical field, hydroceramics are being explored for their potential in drug delivery systems and tissue engineering. Their porosity allows for the encapsulation of pharmaceuticals, which can then be released in a controlled manner, enhancing treatment efficacy. Additionally, the biocompatibility and bioactive properties of certain hydroceramic formulations make them suitable for use as bone grafts or scaffolds in tissue engineering, promoting cell attachment and growth.

Environmental Remediation

Hydroceramics can also play a vital role in environmental remediation efforts. Their ability to absorb pollutants from air and water can be leveraged to clean contaminated environments. For example, hydroceramic-based filters can capture airborne particulate matter or absorb oil spills, aiding in the recovery of natural ecosystems. Their water-absorbing properties are also beneficial for soil amendment, helping to retain moisture in arid soils and reduce erosion.

Implementation of Hydroceramics in Passive Cooling Systems for Sustainable Buildings

In the quest for more sustainable building practices, the construction industry has increasingly turned towards materials and technologies that reduce energy consumption and enhance indoor environmental quality. One innovative approach is the integration of hydroceramics into building designs, particularly for passive cooling systems. This case study examines the application of hydroceramic panels in the "EcoInnovate Building," a modern office complex located in Phoenix, Arizona, designed to showcase cutting-edge green construction technologies.

The EcoInnovate Building incorporates hydroceramic panels within its façade and roofing system. These panels are engineered with high porosity and hydrophilicity, enabling them to absorb moisture from the air during cooler night-time hours. As daytime temperatures rise, the stored water gradually evaporates, absorbing heat from the surroundings and thereby reducing the interior temperature. This natural cooling process minimizes the need for air conditioning, leading to significant energy savings.

The implementation of hydroceramics in the EcoInnovate Building has resulted in a remarkable reduction in energy consumption. Comparative data collected over a year showed a 40% decrease in energy used for cooling compared to a conventional building of similar size and occupancy in the same geographic location. This reduction translates into substantial cost savings and a lower carbon footprint for the building.

In addition to energy savings, the use of hydroceramics has notably improved the indoor environmental quality (IEQ) of the EcoInnovate Building. The natural humidity regulation provided by the hydroceramic panels maintains a comfortable indoor humidity level between 40-60%, optimal for human health and productivity. Furthermore, the gradual release of moisture helps to mitigate the "sick building syndrome" by reducing the buildup of pollutants and enhancing air quality.

The temperature and humidity sensors installed throughout the building recorded an average indoor temperature reduction of up to 5°C (9°F) during peak summer months, without reliance on mechanical cooling systems. This passive cooling effect not only contributes to energy efficiency but also ensures a stable and comfortable indoor climate, even in the face of external temperature fluctuations.

The EcoInnovate Building's energy performance data highlights the efficacy of hydroceramics in green construction. The energy savings realized from the reduced use of air conditioning units have been reinvested

into other sustainability initiatives within the building, such as solar panels and water recycling systems, further enhancing its environmental credentials.

The EcoInnovate Building serves as a tangible testament to the potential of hydroceramics in revolutionizing sustainable construction. The successful implementation of hydroceramic passive cooling systems demonstrates not only the feasibility of reducing energy consumption and improving indoor environmental quality but also the broader implications for sustainable urban development. As the construction industry continues to evolve, hydroceramics stand out as a key material in the transition towards more energy-efficient and environmentally friendly buildings.

Future Directions and Challenges

The exploration and application of hydroceramics have unveiled a wealth of opportunities, yet the journey towards their widespread adoption is accompanied by several challenges and future directions worth investigating. As we stand on the brink of potential breakthroughs in material science, it is crucial to navigate these challenges thoughtfully and explore new avenues for hydroceramic applications. This section delves into the prospective future directions for hydroceramics and the inherent challenges that need to be addressed.

Enhancing Mechanical Strength and Durability

While hydroceramics exhibit commendable mechanical properties, there is an ongoing quest to further enhance their strength and durability without compromising their hydrophilic characteristics. Future research could explore the incorporation of nanomaterials or composite structures that reinforce the ceramic matrix, offering improved resistance to physical stresses and environmental degradation. Addressing this challenge is vital for expanding the application of hydroceramics in structural and high-load-bearing contexts.

Scalability and Manufacturing Processes

One of the significant challenges facing hydroceramics is the scalability of their production processes. Current synthesis methods, while effective for small-scale production, may not be economically viable or environmentally sustainable when scaled up. Innovations in manufacturing technologies that reduce energy consumption, material waste, and overall costs are essential for making hydroceramics a feasible option for widespread use in various industries.

Integration with Existing Systems and Materials

For hydroceramics to achieve broader acceptance and application, strategies must be developed for their seamless integration with existing building systems and materials. This includes ensuring compatibility with conventional construction methods, developing standardized installation procedures, and addressing potential issues related to the interface between hydroceramics and other building components. Collaboration between material scientists, engineers, architects, and the construction industry will be key to overcoming these integration challenges.

Environmental Impact and Sustainability

As with any new material, the environmental impact of hydroceramics throughout their lifecycle—from production to disposal—warrants thorough investigation. Future directions should include assessing the sustainability of raw materials used in hydroceramic production, exploring recycling and reuse pathways, and evaluating the long-term ecological footprint of hydroceramic applications. Ensuring that hydroceramics contribute positively to environmental sustainability is paramount.

Broadening the Spectrum of Applications

Hydroceramics have demonstrated potential in construction, water purification, and biomedical applications. However, their unique properties can be harnessed in numerous other fields. Research into novel uses of hydroceramics, such as in energy storage, sensor technology, or as components in wearable technology, could open new avenues for innovation. Encouraging interdisciplinary research will be crucial in uncovering these novel applications.

Conclusion

Hydroceramics emerge as a material at the confluence of tradition and innovation, imbued with the potential to fundamentally alter the landscape of material science and engineering. As we have seen, their multifaceted nature allows for applications that stretch across industries, from the creation of energy-efficient buildings to advancements in medical technology. Yet, the path to their full integration into the market is strewn with challenges, including the enhancement of mechanical properties, the scaling of production processes, integration with existing systems, and ensuring environmental sustainability throughout their lifecycle. Despite these challenges, the continued exploration and application of hydroceramics hold great promise. With concerted effort in research and development, as well as collaboration across scientific and engineering disciplines, hydroceramics may well provide answers to some of the most pressing issues of our time. As we advance, hydroceramics stand ready not just as a solution for today but as a foundation for a more sustainable and efficient tomorrow.

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