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Smart Materials in Green Architecture: The Role of ETFE and Phase Change Materials in Sustainable Building Design

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Abstract: Given the importance of energy in achieving environmental sustainability in green buildings, one of the most significant solutions is to reduce physical building consumption and instead use renewable energy to prevent the depletion of natural resources and environmental pollution. Utilizing advanced technologies and intelligent systems in architecture is one of the methods that can achieve energy management in buildings and ensure comfortable conditions for the occupants of green buildings.

In the field of future-oriented architecture, it is expected that in the future, materials and technologies developed over the past century will define the different challenges ahead to elevate sustainable development in the building industry. Using solar energy, one of the latest innovations in buildings, and other measures such as ETFE panels (a green roof idea with an intelligent system) and thermochromic materials, which change color to minimize heat exchange between interior and exterior spaces of the building, show that today's world faces energy crises. The use of smart materials tailored to environmental conditions can significantly impact building design and have beneficial effects in terms of compatibility with the environment, increased lifespan of materials, and the adaptability of materials to changing weather conditions, thus aiding in achieving sustainable architecture.

Therefore, this article aims to introduce intelligent materials and their applications and benefits in green building architecture based on library studies. The primary goal is to identify and highlight the most crucial aspects of using intelligent materials and their performance in buildings and how these materials behave and perform in architectural designs. The best way to leverage the benefits of these smart energy-saving materials and management for achieving sustainable architecture will be discussed.

Keywords: Green architecture, Sustainable building, Renewable energy, Phase change materials

1.Introduction

Buildings and living within them have undergone significant changes over the past two decades. It can be stated that our growing population, along with urban life, is accompanied by energy consumption and pollution resulting from human activities. Therefore, preserving the environment is one of the major factors in green architecture, making it one of the crucial architectural trends of the present era, which is addressed in economic, social, and environmental domains.

The concepts of green and sustainable emphasize compatibility with the environment and the permanence of an artificial topic, such as a building, determined by the community. Each community’s persistence is supported by the current and future inhabitants. In this regard, sustainable and environmentally friendly architecture can be realized through advanced and intelligent technologies, where the most advanced models of sustainable and green buildings are placed not only against nature but also in line with environmental facilities and human comfort. A green and sustainable building aims to regulate natural conditions and control factors to optimize space utilization and comfort. This architecture endeavors to maximize the use of natural elements and renewable resources to provide comfortable environmental conditions for its inhabitants. It achieves this by employing advanced technologies and systems harmonized with natural conditions, striving for the highest efficiency in utilizing natural elements and renewable energy resources. This results in environmentally compatible and aesthetically pleasing buildings that offer comfort and environmental benefits (Liu, 2022).

Green architecture is derived from sustainable architecture, and its development has stemmed from the human need to confront the adverse consequences of today's industrial world and the consumption of the current era. The preservation and protection of the world's natural resources, prevention of air pollution, and other environmental pollutions, as well as the protection of physical and mental health, are topics that are increasingly highlighted as a global duty.

2.Green Architecture

Green design is a practical solution to problems that naturally arise before, during, and after the production process. The construction aims to minimize harmful impacts as much as possible. In addition, this practice must have a long useful life and be recyclable and reusable. Green materials should have a long lifespan and be both cost-effective and effective in combating waste and losses, making them better for reuse or recycling.

Currently, as resources are depleting and disappearing, it is time for architects, landscape architects, urban designers, engineers, and building specialists to fundamentally rethink. Specialists must base their skills and expertise on sustainable building design to support and protect the future of children and future generations in this field.

Before anything else, a green building, like any other creation, needs a creator. This means that creating a green building will help and support the individual who lives in it and its surroundings and will lead to their satisfaction and well-being. This need requires careful attention to the following issues in architecture:

Utilizing sustainable resources and focusing on the use of thermal, electrical, and lighting power, as well as daily reuse, create a union and unity that provides the building with structural stability and production. Of course, we must consider that transforming this into the essential structure of human spirit and body will result in mutual dependence and will reveal something extensive about ourselves and our rediscovery of nature. The world of nature is superior to everything else. We must enforce this design and planning because it is only in this way that progress is achieved. This fact will be successful if the group of designers and planners genuinely believe in its merits.

Often, a green building is interpreted as a building with minimal negative impacts on its surroundings. The goal of creating green buildings, based on the above-mentioned principles, is to improve water and air quality and prevent the negative effects of construction on the environment. Currently, energy conservation and the optimization of energy consumption and the use of sustainable energies play no role in the building culture of the country. Additionally, in private residential construction, particularly for the affluent classes, significant amounts are spent on excessive and inauthentic decorations, often referred to as ornamental building, at the expense of other necessary expenses. The motivation for spending these disproportionate amounts on adornment is to achieve grandeur and splendor, ultimately leading to commercial success, especially in the building and selling business. Unfortunately, this issue has become a trend in society, which is concerning.

Figure 1: *Green architecture*

The solution to the problem lies in developing new aesthetic approaches to create transformation and change in public perception and replacing the current degenerate patterns with ecological patterns based on the balance of energy conservation and optimization, and respect for the natural and social environment. This requires that architects strive to guide public taste in constructive and socially beneficial directions instead of following popular and market-driven tastes. Architects can make people believe that climatic and environmental designs are no less beautiful than the current prevalent decorations. Through architecture, society can be informed about the great economic and environmental value of energies that have become renowned for their calm and comfort. From the perspective of artists and architects, these energies can be considered beautiful above all else. The future of the world lies in the discovery of the beauty inherent in clean and life-giving energies. Let's discover the beauty hidden in clean and life-giving energies. Traditional architecture values and the environmental values of traditional architecture in many countries around the world possess significant value in the various ways of optimal use of energy and ecological exploitation of different types of energies, especially the use of sustainable and intangible energies.

The type of materials and construction techniques used in the past, especially those related to the sustainability of the building and the main load-bearing elements of the building, namely walls and roofs, or more generally, horizontal and vertical elements, naturally and automatically had a high capacity for energy storage and thermal balancing in artificial spaces compared to lightweight and low-volume materials currently in use. However, this feature by no means implies that the beauty, comfort, excellent sustainability, and environmental qualities and innovations related to the optimal use of energy in architecture are self-evident, trivial, and devoid of the need for intelligence, creative power, and science and knowledge. Contrary to detailed examination, architectural features indicate a great deal of knowledge and awareness, intelligence and cleverness, and attention to architectural details. There is a significant focus on creating comfortable and pleasant interior spaces, beauty, durability, non-destruction of the environment, and maintaining the quality of life (Vagtholm, (2023)) (Lotfabadi, (2019); Sánchez-García, 2023; Pardo, 2023).

2.1 Principles of Green Architecture

The first principle is the protection of energy, followed by the second principle, which is working with climate. The third principle focuses on reducing the use of new resources, while the fourth principle emphasizes respect for users. The fifth principle addresses respect for the site, and finally, the sixth principle highlights holism.

Green buildings are designed to meet the specific needs of their occupants, providing spaces that enhance health, satisfaction, and productivity. They ensure that the environment inside the building promotes vitality and well-being, creating a harmonious living or working space. These buildings require the prudent use of sustainable architectural solutions, focusing on the integration of non-toxic materials, effective use of resources, and reliance on natural lighting and energy sources. By combining these elements into a cohesive design, green buildings offer significant benefits to both their occupants and the environment.

The building meets the needs of its occupants and ensures their health, satisfaction, contentment, productivity, and vitality. It requires the prudent use of verified sustainable architectural solutions, construction with non-toxic materials, and effective use of materials derived from sustainable natural resources. Additionally, it relies on the sun for daylighting, thermal, and electrical energy, as well as the recycling of materials. The architectural integration of these solutions results in a building that brings pride to its users and serves the natural world.

Some aspects of green architecture include: 1- increasing comfort, livability, and productivity; 2- improving durability, quality, and maintainability; 3- stabilizing internal environmental conditions; 4- saving money by reducing living costs; 5- realizing the options for high-performance solar buildings; and 6- selecting green building materials to play your part in helping protect the environment.

2.2 Examples of Sustainability in Architecture and Green Architecture

Examples of sustainability in architecture and green architecture include utilizing natural energies in daily consumption and using waste materials, particularly wastewater, for producing water needed for green space irrigation. It also involves employing suitable methods to reduce or control wasted energy and optimize energy consumption, using recyclable non-chemical materials that do not conflict with human health, and designing and constructing with materials close to nature. Preventing the negative impacts of buildings and their products on the environment is essential, as is using natural plants as inspiration for living designs in common areas. Additionally, avoiding damage to land conditions to gain more profit, achieving the highest quality of life through reliance on the environment, and implementing land use methods are key factors. Attention to the ecological character of the area, considering the climatic properties of the region, and paying special attention to the effect of light and air in the design of the whole complex and the arrangement of public and private spaces are also important. Finally, an emphasis on mobility and outdoor living plays a significant role in sustainable architecture.

2.3 Green Materials

When selecting green materials, it is important to avoid using chemical materials that are commonly found in mechanical equipment and insulation. Building materials should be sourced locally to reduce the need for transportation, which helps lower energy consumption and overall pollution. Recyclable building materials or products made from natural sources, such as insulation made from cellulose, homeset, multi-layer boards, recycled brick, and plastic products in the form of boards and coverings, should be utilized. Wood products should be sourced exclusively from managed forests that are certified. Additionally, it is crucial to avoid materials that emit pollutants, such as solvent-based paints and varnishes, carpets, adhesives, wood stains, and other building products that release volatile organic compounds (VOCs).

Since the early 1980s, the scope of building design and construction has witnessed new innovations daily in the field of more efficient and high-performing materials. With continuous progress, the capabilities of materials have increased daily, and humanity has consistently seen the introduction of new materials into the construction industry. Materials used by humans throughout history and past ages have played an undeniable role in shaping the mental space and consequently the life of humans. Perhaps this is why some scholars have labeled human life periods based on the predominant material used during those times as the Stone Age, Bronze Age, Iron Age, Composite Age, and finally the present era as the Age of Smart Materials. Therefore, there has always been a close and unbreakable historical link between construction materials and architecture until the 20th century when the role of materials and technologies in architecture became more significant. In architecture, terms such as Smart, Intelligent, and Adaptive are used to describe structures and materials that include sensors and actuators, which can adapt to external stimuli such as loads and environmental changes. Smart materials are a new term for materials and products that have the ability to understand and process environmental events and respond appropriately. In other words, these materials have the ability to change and can alter their shape, form, color, and internal energy in a reversible manner in response to physical or chemical influences from their surroundings. Smart architecture is dynamic; it means that its main functional parameters change according to need, demand, and changing conditions. A smart architecture can also, like a living system, learn from experiences and use them in new situations, ensuring system dynamism and self-organization.

The main characteristics of smart architecture in green materials include adaptability, dynamism and activity, flexibility and compatibility with the environment, as well as responsiveness and reactivity. In this article, an effort has been made to identify materials that align with green and sustainable architecture, with two of these materials being analyzed in detail.

2.3.1 ETFE

ETFE (see Table 1) is a highly durable, lightweight polymer material widely used in green architecture, especially for roofing and building facades. It allows high light transmission, which helps reduce the need for artificial lighting. Its ability to be inflated and dynamically change transparency makes it ideal for large, flexible spaces. ETFE is also highly resistant to environmental pollution, weather conditions, and UV rays, ensuring a long lifespan with minimal maintenance. ETFE sheets, which are air-inflated cushions, consist of 2 to 5 layers of ethylene tetrafluoroethylene (ETFE) polymer. These ETFE sheets, formed through the extrusion process (where molten

Table 1: *Key Properties of ETFE*

Property	**Description**	**Benefits in Sustainable Architecture**
Material Type	Ethylene tetrafluoroethylene (ETFE)	Lightweight polymer used as a roofing membrane or building facade material
Weight	305 grams per square meter (200 micrometers thickness)	Light load reduces structural demands, lowers transportation emissions
Light Transmission	87-94% visible light, 83-88% UV transmission	Allows natural daylighting, reduces need for artificial lighting
Durability	Lifespan of over 30 years, UV and weather-resistant	Low maintenance, high longevity, suitable for varied climates
Transparency Control	Can change transparency based on air pressure between layers (e.g., matte to semi-transparent)	Dynamic shading and glare control, improves occupant comfort
Recyclability	Recyclable after use	Reduces landfill waste, aligns with circular economy principles

polymer is shaped into the desired form under high pressure), emerge as thin films held by an aluminum frame attached to the building's skeleton. This lightweight and transparent membrane can only withstand tensile stress and handles the external shell's weight and the system's minimum structural load, approximately 220 Pa. ETFE sheets provide excellent insulation for curved and domed structures.

The material offers several advantages, including a very low weight load of 305 grams per square meter with a thickness of 200 micrometers. It provides high transmission of light and UV waves, along with excellent chemical resistance to acids and alkalis. Active shading, superior thermal insulation, and facilitation of natural ventilation are among its benefits. The material is environmentally friendly and highly energy-efficient, with the ability to cover large openings in various shapes. It also features self-ventilation during fire incidents, exceptional durability, no impact from air pollution, and a lifespan of over 30 years.

2.3.1.1 Color, Transparency, and Solar Control

Due to the high light transmission capability of ETFE roofs and the clarity of these roofs, it is highly desirable in applications where visibility of the spectrum of visible light is required. Additionally, colored films can be used. ETFE sheets allow 87-94% of visible light (380-780 nm) to pass through, while the ultraviolet light transmission range (320-380 nm) is also very high (83-88%). It should be noted that ETFE sheets can help reduce energy consumption in buildings, despite their high absorption of ultraviolet rays. The sheets' ability to change transparency and allow or block light as desired is an additional feature. This allows ETFE sheets to be printed with various patterns to reduce light absorption while maintaining transparency. Furthermore, different patterns can be printed on ETFE sheets, and despite the sheets being white, their transparency can be adjusted. The pressure change between the layers can alter the transparency level. This adjustment can create different visual effects, from matte to semi-transparent images.

ETFE sheets can be inflated, meaning they can be engineered into parts and roofs approximately 4.5m wide and up to 1.5m long for larger parts. Larger openings typically require cables or reinforcement grids.

When inflated, several layers can be joined together by air pressure differences to form a single structure. Smaller cushions can be connected and inflated by a single pump. Compared to glass structures, ETFE has a much lower weight and greater flexibility (with a maximum deflection capacity of 15%). Therefore, it is highly desirable for large, flexible spaces.

2.3.1.2 Maintenance

Unlike fabric structures, ETFE sheet is an extruded material, meaning its surface is very smooth. This smoothness, along with ETFE's anti-adhesive properties, prevents the attraction of dirt and dust and any kind of pollution, such as bird droppings, from adhering to its surface. The exterior surface of ETFE roofs does not need cleaning. The internal surface, depending on the level of indoor pollution, may require cleaning every 5 to 10 years. As a result, accessing the roof (which incurs high costs and time for cleaning) can be economically managed. Despite the fact that ETFE sheets are very durable, they can still suffer minor damage. If they do, they can be repaired easily. Any significant damage requires internal access; however, the damaged section can be replaced easily and promptly, with appropriate parts and materials available as needed.

2.3.2 Phase Change Materials (PCMs)

Phase change materials (PCMs) are substances that store and release large amounts of energy during a phase change (e.g., from solid to liquid). These materials are integrated into building components like walls, ceilings, or floors to regulate temperature. When the indoor temperature rises, PCMs absorb heat and melt, preventing overheating. When the temperature drops, they release stored heat by solidifying, stabilizing the indoor climate. Phase change materials (see Table 2) have the ability to change phases (e.g., from solid to liquid) within a relatively constant temperature range. Additionally, the phase change process in these materials usually involves the exchange of a high volume of energy, referred to as the latent heat of phase change. This high heat exchange occurs harmoniously with nature and automatically and intelligently in response to ambient temperature changes. Given these characteristics, these materials have become a unique energy storage capacity for various applications.

These materials are widely used in numerous industries, including telecommunications, transportation, automobiles, satellites, medicine, textiles, greenhouses, and other fields. The first reports of using these materials in buildings emerged around 1940. Since the 1980s, their use in buildings has been extensively studied, and today, their application in the construction industry holds a special position (Zalba B., 2023; Hawes, 1993). These materials can be used in buildings and in separate components for heating and cooling applications, including shutters, sun-facing walls, gypsum boards, underfloor heating systems, ceiling panels, and Trombe walls.

According to the results of a study, the use of phase change materials leads to an increase in room temperature and the storage of approximately 19% energy. Additionally, the use of this material improves thermal comfort conditions by reducing the magnitude of indoor air temperature fluctuations and maintaining the room air temperature closer to the desired level for a longer period.

2.3.2.1 How Phase Change Materials Work

Materials in nature exist in three states: solid, liquid, and gas. When materials transition from one phase to another, they absorb or release a certain amount of heat, known as latent heat. For example, a solid material absorbs heat and, after melting, transitions to a liquid state, releasing a high volume of energy (referred to as latent heat of fusion). Phase change materials have this property where they maintain their

Table 2: *Key Properties of Phase Change Materials (PCMs)*

Property	**Description**	**Benefits in Sustainable Architecture**
Material Type	Organic/inorganic compounds, such as paraffin, salt hydrates, fatty acids	Thermal energy storage material used in building envelopes and systems
Phase Change Temperature	Typically between 20-32°C, depending on material and application	Can maintain interior temperature comfort by absorbing and releasing heat
Energy Storage Capacity	Stores up to 190 kJ/kg of energy during phase change (e.g., solid to liquid or liquid to solid)	Reduces peak energy loads, supports passive heating and cooling systems
Heat Storage Density	5 to 14 times greater energy density compared to traditional thermal storage systems (e.g., water)	Requires less material for the same amount of energy storage
Application Areas	Walls, ceilings, floors, green roofs, underfloor heating, Trombe walls	Improves thermal comfort, reduces need for mechanical heating/cooling
Durability	Long-lasting performance, does not degrade significantly over time	Can be incorporated into building components for long-term energy efficiency
Recyclability	Can be re-used in various building components or systems	Supports circular economy, reduces the need for virgin materials
Environmental Benefits	Reduces energy consumption, stabilizes indoor temperatures	Cuts down on HVAC usage, lowering energy bills and emissions

state within a specific temperature range for an extended period.

This means that these materials act as thermal energy storage systems. When the environmental temperature rises, these materials absorb heat and undergo a phase change (melting), thereby preventing further temperature increase in the surrounding environment. Conversely, when the temperature drops, these materials release the stored heat and transition back to their solid state (freezing), thus maintaining a stable temperature in the environment.

In essence, phase change materials resist temperature increases in the surrounding environment due to their phase change properties, absorbing significant amounts of latent heat over several hours. This process not only increases the material's temperature but also stores energy efficiently. When the environmental temperature decreases, the phase change material releases the absorbed heat, reverting to its solid state and continuing the heat exchange process (Mondal, 2008).

This behavior can be well observed in Figure 2, where the temperature changes and heat absorption occur continuously within the material, maintaining a stable temperature. This latent heat absorption process is similar to the energy storage mechanism in the phase change region.

In phase change materials used in building envelopes, if the selected material has a melting temperature within the temperature range of the same region around noon, the phase change process can occur during the day around noon when the ambient temperature reaches its maximum. Therefore, after the environment heats up and reaches its maximum temperature, the phase change material in the envelope also heats up and reaches its melting point. However, from this point onward, the material continues to absorb thermal energy from the environment but resists increasing its own and the surrounding temperature, maintaining the temperature at the melting point. This process continues until the entire phase change material transforms from solid to liquid, which usually takes several hours. Once the phase change materials have completely melted, their resistance to temperature increase also disappears, but this happens when the peak heat of the day has passed, and the environment has stopped its heating trend. Thus, by using these materials in the building envelope, we have managed to reduce the thermal load of the environment during peak heat hours.

The opposite happens during the solid formation process. Despite the cooling of the air during the night, the phase change material, after reaching its freezing point, resists the temperature drop due to the release of latent heat and the transformation from liquid to solid. This material, through releasing the absorbed

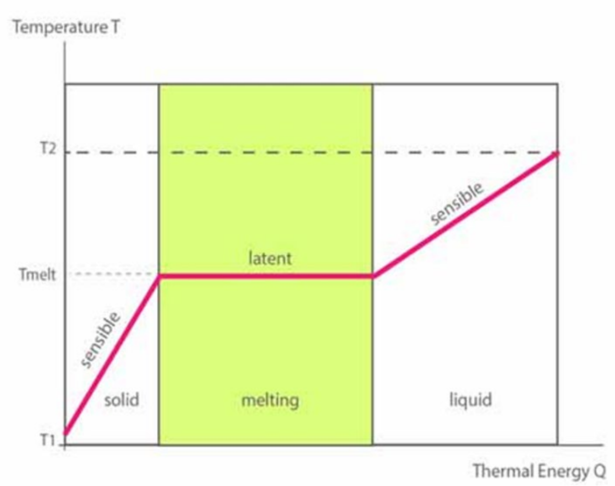

Figure 2: *Phase Change Material Performance (Rathore, 2022)*

heat during the day, prevents the decrease in its own and the surrounding temperature and thereby reduces part of the cooling load of the environment during the cold hours of the night.

Therefore, with the intelligent selection of phase change material and its application in the building envelope, it is possible to reduce energy consumption for cooling and heating during peak hours without the use of additional mechanical equipment. By using the natural capability of this material for phase change, energy consumption is reduced by mitigating temperature fluctuations in the building and providing moderate temperatures during peak hot or cold hours.

One of the important points in using phase change materials is their high density in storing thermal energy compared to other thermal storage methods. For example, a type of phase change material with a melting point of 45 degrees Celsius stores 190 kJ of energy per kilogram. To store the same amount of energy with water, we would need to heat it from 45 to 190 degrees Celsius. A comparison of temperature changes for storing the same amount of energy shows that phase change materials (PCMs) exhibit a temperature fluctuation of around 20°C, water around 40°C, and concrete approximately 180°C.

The melting point of phase change materials varies in a range of 30 to 90 degrees Celsius, which means that the materials that change phase at a range of 20 to 32 degrees Celsius have a better capacity for application in building cooling and heating. In addition to water [5], there are about 500 types of natural and synthetic phase change materials, which have different phase change temperatures. By selecting the appropriate phase change material based on the type of climate zone and the season, this material can be used to moderate the temperature of the indoor air and therefore save on heating and cooling energy consumption.

The use of phase change materials in buildings, considering that the phase change materials maintain their application over a long period, prevents the loss of these materials in different phases. Phase change materials available in the market are used for the consumption of buildings in three states: liquid, solid, and microencapsulated. Additionally, hard panels made of high-density polyethylene (HDPE) plastic contain these materials. To include real-case examples of using ETFE and PCMs, we can mention The Eden Project in Cornwall, UK, which uses ETFE cushions in its biomes to provide thermal insulation and natural light transmission, reducing structural weight, material costs, and energy use for lighting, making it a model for sustainable architecture. Capital Tower in Singapore was the first building in the country to offer WIFI and has since evolved to prioritize energy efficiency and employee well-being. Its advanced HVAC system recovers cool air to reduce energy use, and smart lighting along with IoT sensors monitor air quality, temperature, and CO2 levels to enhance occupant comfort and safety.

2.3.2.2 The use of phase change material in solar systems

One of the capacities of phase change materials is for energy storage in solar buildings that have the ability to collect solar energy. By using phase change materials in such systems, the high volume of solar energy during the day is stored and can be used for heating at night (IP, 1998) (Farid M. M., 2004). The phase change materials in these systems are usually placed in thin layers with the arrangement of plates to store and then transfer heat. These materials work indirectly with water. The method in these systems is such that the collected energy by the collectors during the day causes the warm liquid to move (usually water). This warm liquid transfers its heat to the phase change material plates and then returns. This phase change material delivers this hidden heat to the warm liquid and receives the cold liquid during the night hours, thereby replacing the warm water in the system. The phase change material itself transfers its temperature reduction process (from liquid to solid) to the warm water, causing the warm water to heat up, and then this water is used for building heating purposes. To increase the efficiency of such systems, it is necessary to use techniques that maximize the heat transfer process, and most studies are conducted in this field.

3 The impact of smart materials in green buildings

3.1 Environmental features of ETFE

The energy consumption in the production process of ETFE sheets is very low, and its complete structure weighs about 50 to 90 percent less than similar constructed materials with comparable weight characteristics. Of course, the ETFE system requires more protection to maintain its cover. Part of its materials are made from recycled materials, and at the end of the project, the entire system can be recycled to the construction site to be reused. The long life span and low maintenance and repair costs turn ETFE into a suitable solution in sustainable architecture. The green and sustainable architect can use the smart and thermal cycling light characteristics of ETFE to change the space and functionality of buildings. These capabilities and features make ETFE sheets unique.

3.1.1 Air Dryers

Air dryers can easily absorb air humidity, which is blown into the inside of the pillows. The use of these moisture absorbers is recommended in high humidity environments.

3.1.2 Fire

ETFE sheets have low flammability and are self-extinguishing. In the event of a fire, the ETFE cushions automatically evacuate the fire because the hot air mass causes the ETFE sheet to gather and move away from the heat source, allowing the fire to go out. Since the amount of material present in the roof is minimal, molten droplets of the sheet do not drip down during a fire.

3.1.3 Acoustics

A ceiling with relatively good sound insulation. This means that the sheet acts as a sound absorber for the room and increases the perception and understanding of sounds in the indoor environment.

3.1.4 Thermal Insulation

The U-value of a three-layer cushion is equivalent to 1/96 W/m, which is much higher than the horizontal glass with 3 layers. This means that the vertical glass manufacturers provide figures that are much higher. The characteristics of the cushions, with the addition of layers that have their own light characteristics, can improve the insulation properties.

3.1.5 Durability

ETFE sheet is resistant to UV rays, environmental pollution, and weather conditions. This material, whether in the laboratory or in the external environment, has been tested and no degradation or reduction in resistance has been observed. ETFE does not discolor over time and remains intact. It is claimed that this material has a lifespan of more than 40 years.

3.1.6 Structure

ETFE is used as a replacement for steel cables and does not require any structural support. To achieve wider spans, it can be reinforced with additional cable support.

3.1.7 Water and Steam Insulation

The cushions act not only as a water and steam barrier but also as an insulation for fluoropolymer sheets.

4. The impact of phase change materials on green buildings (Application of phase change materials on green roofs)

Green plant coverings on roofs can be recognized as a passive technique aimed at reducing energy consumption and improving the quality of the surrounding building air. This function can be effective in both winter and summer through heat protection and cooling prevention and the creation of shade. This leads to urban heat island reduction, energy conservation, and internal management of heat rejection. Despite the importance of this topic, the use of green roofs is often limited to energy saving and blocking heat from the sun during the day and releasing it at night. In this context, it is necessary for the materials and resources to be able to store and conceal heat for a long time.

In other words, green roofs that store hidden heat improve the efficiency of the green roof by providing heat in winter and creating shade and cooling in summer. This results in a reduction of the total thermal load required for the building and adding phase change materials in the internal layer of the building intensifies these positive effects.

4.1 Thermal performance of green roofs

The transfer of thermal charge in green roofs is controlled by four mechanisms: shading, thermal insulation, evaporation and transpiration, and thermal mass.

Overall, green roofs reflect about 22 percent of solar radiation, approximately 6 percent of which is reflected through evaporation. Additionally, about 13 percent is transferred to plants and soil, with only 13 percent transferred to the soil alone (Hui, 2009). The effects of green roofs can be divided into two aspects:

The direct impact on the building (internal effect): In this case, the issue is the transfer of heat from the roof inside the building, which reduces this heat exchange and prevents additional energy consumption in the building.

The indirect impact on the surrounding environment (external effect): In this case, the issue is the transfer of heat from the roof to the surrounding environment, which leads to an increase in the cooling load and creates urban heat islands, reducing the temperature and cooling the building's environment.

4.2 Phase Change Materials

As mentioned, phase change materials are used for latent heat storage. This process involves absorbing and releasing heat energy at a nearly constant temperature during the phase change process. PCM can store approximately 5 to 14 times more heat energy than sensible heat storage systems. Therefore, due to the high energy density and the higher energy storage capacity with less temperature fluctuation, PCM systems are more efficient. Despite their specific challenges, they can be applied to walls, ceilings, and floors (PCM). By incorporating these materials, the room's air temperature is significantly reduced and thus improves thermal comfort and reduces energy consumption.

4.3 Objectives of Phase Change Materials in Buildings

The goal of using PCM in buildings is twofold: increasing the building's thermal inertia and reducing the need for heating and cooling, which results in increased energy savings. PCM use can create heating and cooling systems through solar energy and natural ventilation.

4.4 Thermal Performance of Phase Change Materials

It is worth mentioning that the recent use of phase change materials in building applications has been considered for significant energy savings. The performance of phase change materials in buildings is such that during the day, by absorbing heat and as a result, some of the building's thermal energy penetrates into the building wall and melts, and during the night, as the air cools down, they start to freeze and prevent the internal space from becoming warm, and the stored heat is released back to the outside. This reduces the range of external air temperature fluctuations after passing through the wall. This also causes the peak temperature to shift, so it will reduce consumption at peak times, requiring less cooling systems (D. Zhou, 2012).

Since keeping heat and conserving warmth in cold seasons in this climate is vital, the potential for energy savings is provided by using green roofs up to 20 percent if phase change materials are applied along with green roofs. This results in a 36 percent savings due to the short period of warmth in this climate. The high potential of the green roof indicates that it has a high capacity for reducing cooling loads and reducing the need for additional cooling equipment. This is also important because it significantly reduces the need for primary investment in cooling systems in this climate, following economic and environmental considerations. Equipment and costs associated with the transfer of cooling in buildings are eliminated, and on the other hand, the amount of energy required for cooling, which relies on a fossil source, is reduced to zero. This will have an effective role in reducing CO2 emissions.

5. Comparison of ETFE and Traditional Materials

To strengthen the argument for ETFE as a smart material in sustainable building design, it is essential to compare it with traditional materials like glass and concrete. ETFE (Ethylene Tetrafluoroethylene) is known for its lightness (approximately 1% of the weight of glass), superior thermal insulation, and greater flexibility. Unlike glass, which is heavy and prone to shattering, ETFE is extremely durable and resistant to weathering, pollution, and UV light. Additionally, ETFE's transparency can be adjusted for solar control, making it more adaptable to changing environmental conditions. ETFE also requires minimal maintenance due to its self-cleaning properties, while glass requires regular upkeep. In terms of environmental impact, the production of ETFE consumes significantly less energy, and it is fully recyclable, which makes it a more sustainable choice in comparison to glass and other traditional materials like concrete.

6. Challenges and Limitations of Smart Materials

While the initial cost of ETFE can be higher than traditional materials, its overall cost-effectiveness is demonstrated through reduced structural requirements, lower maintenance costs, and energy savings. ETFE structures often require less supporting steelwork due to the material's lightweight nature, leading to cost reductions in the building's framework.

For PCMs, the initial investment is offset by long-term energy savings from reduced heating and cooling demands. Studies have shown that buildings utilizing PCMs can achieve energy savings of up to 20–30% in certain climates. Additionally, government incentives for energy-efficient construction can further improve the economic feasibility.

Additionally, availability can be an issue, as these materials may not be as readily accessible in all regions, potentially leading to increased transportation costs and carbon emissions. Technical limitations also exist; for example, ETFE is primarily effective in tensile structures and may not be suitable for all building types. Similarly, PCMs require careful integration into building designs to maximize their effectiveness, and their performance can vary based on climate and application.

6. Conclusion

In this paper, we explored the fundamental principles and importance of green architecture in addressing the environmental challenges posed by modern urbanization and industrialization. Green architecture, with its focus on energy conservation, sustainable materials, and human comfort, emerges as a vital solution for reducing the negative impacts of traditional construction practices. The integration of advanced technologies and eco-friendly materials, such as ETFE and phase change materials, demonstrates how buildings can achieve a balance between environmental sustainability and the well-being of their occupants. Through intelligent design and the use of renewable resources, green buildings not only optimize energy efficiency but also promote healthier and more aesthetically pleasing living spaces.

Moreover, this paper highlighted the potential of green architecture to transform public perceptions and building practices by emphasizing the value of environmental harmony and resource conservation. The use of innovative materials and techniques can significantly reduce energy consumption, minimize CO2 emissions, and mitigate the effects of climate change. By promoting the adoption of sustainable architectural practices, this approach fosters a long-term vision for ecological balance and improved quality of life. Ultimately, green architecture sets the foundation for a future where buildings are not only functional but also environmentally responsible and aligned with the broader goal of sustainability.

Smart materials like ETFE and PCMs have significant potential in green building design. ETFE offers flexibility, lightness, and durability, while PCMs excel in energy storage and reducing temperature fluctuations. To effectively incorporate these materials, architects should consider lifecycle impacts, installation costs, and potential challenges. Future projects should prioritize their use in climates where their properties can be fully utilized. Combining ETFE with other energy-saving systems enhances overall building performance and sustainability. These materials should be viewed as integral components of sustainable architecture strategies rather than standalone solutions.

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