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PRACTICAL WORK REPORT

IMPLEMENTATION OF SMART MATERIALS TO SUPPORT EFFICIENT & SUISTANABLE GREEN BUILDINGS

INTERNATIONAL COURSE PROGRAM (ICP)

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PREFACE

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CHAPTER 1

INTRODUCTION

1.1 Background

Green building and smart building are two key approaches in the world of modern construction aimed at creating sustainable buildings. Although both share the same goals efficiency and sustainability the main difference lies in their focus and the methods used in their implementation.

Green building prioritizes environmental aspects with the primary goal of minimizing negative impacts on nature. This is achieved by reducing the use of energy, water, and environmentally unfriendly building materials.

Green buildings prioritize the use of renewable energy sources such as solar panels, water efficient management, and recyclable building materials. Passive design elements, such as natural ventilation and natural lighting, are also key focuses for reducing energy consumption.

The rapid growth of the construction sector has had a significant impact on energy consumption, the use of natural resources, and rising carbon emissions. The building and construction sector is one of the major contributors to global energy consumption and carbon emissions, highlighting the urgent need for more energy efficient and sustainable building technologies. (Cousins, 2022). Buildings are among the largest contributors to the consumption of electricity, water, and materials that have the potential to cause environmental pollution. For centuries, humans have built homes, buildings, and infrastructure using relatively simple materials such as stone, wood, steel, and concrete which have served as the backbone of construction across the globe. Cement and steel production are among the world's largest contributors to greenhouse gas emissions. Every year, billions of metric tons of carbon dioxide are released into the atmosphere to meet global construction needs. Therefore, the concept of Green Building is increasingly being adopted as an effort to create buildings that are environmentally friendly, energy efficient, healthy, and sustainable.

One innovation supporting the implementation of Green Building is the use of Smart Materials. Smart Materials are materials capable of automatically responding to environmental changes such as temperature, light, pressure, humidity, or electric current, thereby improving a building's energy efficiency and comfort. Examples include electrochromic glass that can regulate the intensity of sunlight, self healing concrete capable of repairing cracks on its own, and phase change materials (PCMs) that can store and release heat.

The implementation of Smart Materials in modern buildings is expected to reduce energy consumption for cooling and lighting, extend the building's lifespan, lower maintenance costs, and support environmental sustainability principles. Therefore, it is necessary to discuss how Smart Materials can be implemented to support efficient and sustainable Green Buildings.

1.2 Problem Statement

The Problem statement for this report are:

1. What are Smart Materials and Green Buildings?
2. What types of Smart Materials can be used in green buildings?
3. How do Smart Materials help improve energy efficiency and sustainability in buildings?

4. What are the benefits and challenges of using Smart Materials in green buildings?

1.3 Objectives of the Project

The Objectives of this Project are:

1. Explain the concepts of Smart Materials and Green Building.
2. Identify the types of Smart Materials used in buildings.
3. Analyze the implementation of Smart Materials in supporting building efficiency and sustainability.
4. Understand the benefits and challenges of applying Smart Materials in Green Building.

1.4 Research Benefits

The benefits for writing this report are:

1. Theoretical Benefits

   Provides insights and references regarding the relationship between Smart Materials and Green Building.

2. Practical Benefits

   Serves as a guide for planners, contractors, and building managers in selecting efficient and sustainable materials.

CHAPTER II

LITERATUR REVIEW

2.1 Green Building

According to the Green Building Council Indonesia (GBCI), a green building is one that, from the planning, construction, and operation stages through to maintenance, takes into account environmental considerations, conservation, and the reduction of natural resource use.

According to the Environmental Protection Agency (EPA) in the United States, a green building is the practice of creating structures and using processes that are environmentally responsible and efficient in their use of resources throughout the building's life cycle.

According to the World Green Building Council, a green building is a building that, through its design, construction, or operation, can reduce or eliminate negative impacts and create positive impacts on our climate and environment.

Green Building refers to sustainable buildings that incorporate environmentally responsible and resource efficient structures and processes throughout the building's life cycle. (Widyawati, 2019). (Adeswastoto et al., 2023) states that green building is an approach to designing, constructing, and operating buildings that takes into account their impact on the environment and human health, thereby improving efficiency and reducing the negative environmental impact of buildings. In addition, (Xavieri Linggo & Sutandi, 2023) emphasize that green building is a concept of sustainable development that applies the principle of resource conservation from the design phase through to the demolition of a building.

2.2 Green Building Principles

In general, green building principles cover various aspects aimed at reducing environmental impact and improving resource efficiency (Roshaunda et al., 2019). Some of these principles are as follows:

1. Energy Efficiency

   Green buildings emphasize optimal energy use, such as maximizing natural light and air circulation and minimizing the use of electricity. Examples include the use of solar panels.

2. Water Conservation

   Green buildings also prioritize water recycling systems or the most efficient use of water possible. This includes strict water usage monitoring systems, rainwater harvesting, efficient irrigation for plants, and responsible wastewater management.

3. Use of Environmentally Friendly Materials

   The use of materials sourced from renewable resources or recycled materials, as well as prioritizing local materials to reduce the ecological impact caused by long distance shipping.

4. Indoor Health and Comfort

   Ensuring a healthy indoor environment for building occupants through clean air circulation, adequate natural lighting, and minimizing pollutants and disruptive noise.

5. Building Environmental Management

   From the construction phase through to operations, green buildings prioritize environmental sustainability, waste management, and innovation in living house design.

2.3 Smart Materials

2.3.1 Meaning of Smart Materials

Smart materials are types of materials whose physical or chemical properties can change automatically when exposed to external stimuli, such as temperature, light, pressure, or an electric current. These responses can take the form of changes in shape, color, strength, or conductivity. These characteristics allow smart materials to function not only as passive elements in building structures, but also as active systems that can adapt to changes in the environment.

According to (Brieno, 2024) Smart materials are characterized by their ability to respond to stimuli such as temperature, light, pressure, or magnetic fields, resulting in changes in their mechanical, electrical, or optical properties. The study titled "Embedding Intelligence in Materials for a Responsive Built Environment" by (Schwartz & Lagerwall, 2022) states that smart materials are materials capable of sensing and responding to changes in the environment, thereby enabling buildings to automatically adapt to surrounding conditions. Smart materials are increasingly considered important components of sustainable development because they can perform adaptive functions such as thermal energy storage, self repair, sensing, and environmental response without relying entirely on conventional mechanical systems. (Nicolay et al., 2023)

2.3.2 Types of Smart Materials for Green Buildings

The types of Smart Materials for Green Buildings are:

1. Electrochromic Glass

Electrochromic glass is a type of smart glass based on a multilayer electrochemical device capable of reversibly controlling the transmission of visible light and near infrared (NIR) radiation by applying a low voltage electrical potential (1–5 V). Structurally, an electrochromic device consists of five main thin layers sandwiched between two conductive glass substrates: two layers of Transparent Conductive Oxide (TCO), such as Indium Tin Oxide (ITO) an electrochromic active layer; an ion conductor or electrolyte; and a counter electrode (counter electrode). Changes in the optical properties of this material are based on redox reactions as well as the processes of intercalation (insertion) and deintercalation (extraction) of dissolved cations such as Li^+ or H^+ into the crystal matrix of the active material. One of the most commonly used cathode materials is tungsten trioxide (WO_3) in which the injection of electrons and ions into its structure triggers a change in the valence of tungsten ions, altering the color of the glass from clear and transparent (bleached state) to dark blue (colored state).

The main advantage of this technology is its bistability, whereby the system consumes electrical power only during the color change transition process and does not require a continuous current to maintain a specific level of darkness. Various studies in the literature show that integrating electrochromic glass into building facade systems can reduce daily energy consumption in HVAC and artificial lighting systems by up to 20–30% through adaptive control of solar thermal radiation and natural lighting (daylighting). Recent developments in electrochromic smart windows demonstrate their potential to dynamically regulate both solar radiation and visible light, making them promising technologies for improving building energy efficiency and indoor comfort. (Zhao et al., 2025). Examples: Glass partition walls in meeting rooms, executive privacy areas, or intensive care units (ICUs) in hospitals. The glass can switch from transparent to opaque/dark in a matter of seconds to maintain visual privacy, replacing conventional fabric curtains that are prone to accumulating dust and bacteria.

Figure 2. 1 Example of Electrochromic Glass Application

2. Living Materials

Living Materials, or Engineered Living Materials (ELMs), are artificial composite materials that combine an abiotic matrix (such as hydrogels, cement, or polymers) with living biological cells (such as bacteria, fungi, algae, or mammalian cells). Unlike conventional materials, which are passive, ELMs possess the dynamic properties characteristic of living organisms: they are capable of responding to their environment, growing, self healing, and continuously adapting.

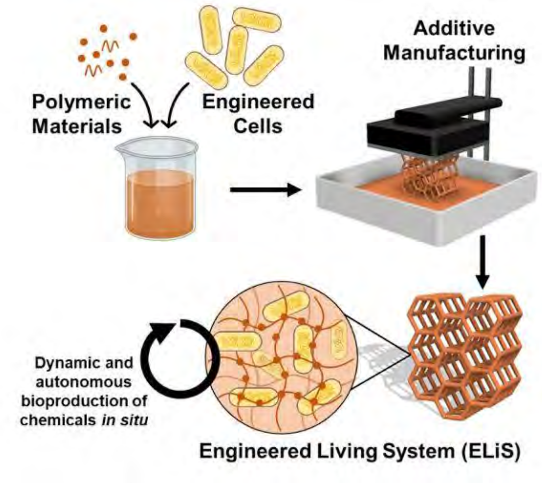

Figure 2. 2 Scheme for the Development of the Engineered Living System (ELiS)

In the fields of sustainable manufacturing and construction, fungal roots or mycelium are used as substitutes for Styrofoam and building insulation boards. Companies like Ecovative Design grow mycelium on agricultural waste such as straw or rice husks until it forms a dense, strong mass, which is then dried. In addition, the development of bio based textiles (bio leather) also utilizes bacterial cellulose cultures from fermentation processes to create an environmentally friendly and fully biodegradable alternative to animal leather. In the fields of green architecture and healthcare, living materials open up the potential for integrating active biological functions. In the architecture sector, paints and building facade coatings embedded with photosynthetic microalgae are capable of absorbing carbon dioxide from the surrounding air and producing oxygen when exposed to sunlight. Meanwhile, in the medical field, translucent hydrogels filled with probiotic bacterial cultures are specifically designed as dressings for chronic wounds. These dressings can detect chemical changes or pH levels in infected wounds and automatically release antimicrobial compounds to accelerate the healing process.

Figure 2. 3 Scheme for the Application of Living Materials in Building Structures

3. Phase Change Materials (PCM)

Phase Change Materials (PCM) are smart materials capable of absorbing, storing, and releasing latent thermal energy as they undergo phase changes such as from solid to liquid or vice versa—in response to changes in ambient temperature. The integration of PCM into building components can improve thermal stability by absorbing excess heat and releasing stored energy when surrounding temperatures decrease, thereby reducing peak cooling demand. (Poudhar & Ghosh, 2025).

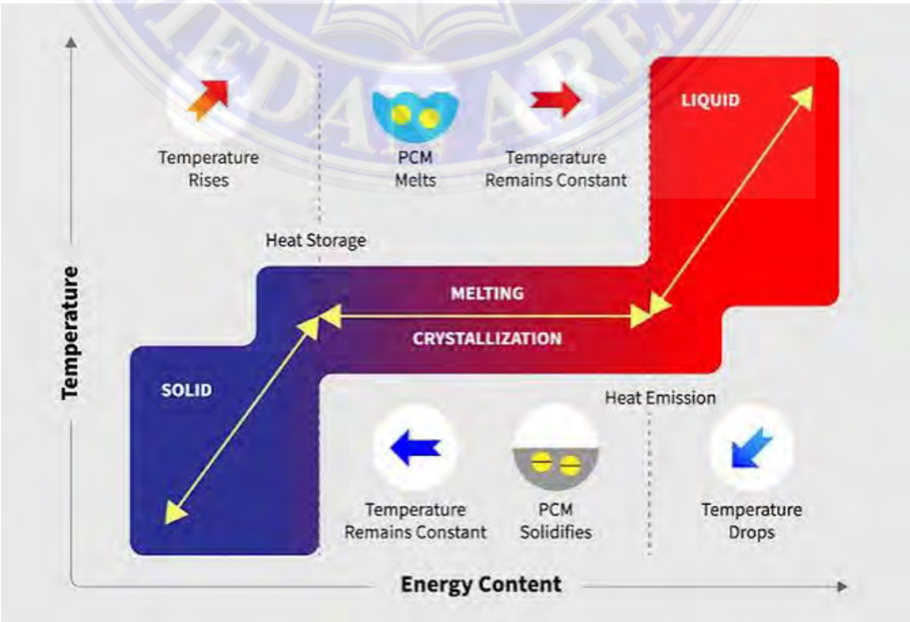

Figure 2. 4 Working of Phase Change Materials

In the field of modern architecture and construction, PCM technology is widely integrated into building envelope elements such as walls, ceilings, and interior panels, and is utilized in thermal energy storage systems. The close connection between PCM and the concept of green building lies in its ability to passively maintain interior temperature stability; during the day when solar radiation increases, PCM absorbs excess heat fluctuations, thereby mitigating indoor temperature spikes. This thermal regulation mechanism significantly reduces the cooling load and lowers air conditioning (AC) energy consumption, which ultimately contributes directly to energy efficien cy and the effectiveness of environmentally friendly building designs.

2.4 The Concept of Suistanable Development

This concept has three pillars: environmental, economic, and social. Green buildings are a tangible manifestation of the application of these three pillars in the construction and urban planning sectors, where the design, construction, and operation of buildings focus on environmental conservation, long term cost efficiency, and the health of their occupants.

1. Environmental Pillar

   Protecting natural resources, reducing carbon emissions, preserving biodiversity, and preventing ecosystem damage. Practices that can be implemented in green buildings include conserving water and electricity, utilizing natural lighting and cross ventilation, and using eco friendly or recycled materials to reduce the carbon footprint.

2. Economy Pillar

   Creating stable financial growth, improving cost efficiency, and opening up new market opportunities without depleting future resources. Examples of its application in green buildings include reducing long term operating costs (such as significantly lower electricity and water bills), increasing the resale value of assets or properties, and ensuring high durability.

3. Social Pillar

   Ensuring fairness, health, and safety, and improving the quality of life for the general public and surrounding communities. Its application in green buildings includes creating clean and healthy air circulation that benefits the physical and mental well being of building occupants, and providing comfortable, safe spaces that support work productivity and the quality of daily life.

2.5 Previous Research

This previous research served as one of the author’s references in conducting this study, thereby enabling the author to enrich the theoretical framework used in analyzing the research conductedTo avoid duplicating previous studies and to strengthen the originality of this research, the author reviewed several previous studies relevant to the topic under investigation. Based on the literature review, there are several studies that focus on this project study is based on a previous study the type of research, the theories used, the research methods, and the primary references are explained below.

Tabel 2. 1 Previous Research

No	Researcher	Research Title	Conclusion
1.	Yanru Li, Kwok Wei Shah, Wenxin Li, Teng Xiong	Experimental investigation on indoor thermal environment improvement and energy saving of electrochromic window under Singapore's tropical climate	A study by (Y. Li et al., 2023) published in the Journal of Building Engineering conducted experiments on electrochromic windows under Singapore's tropical climate conditions. The study was conducted using two climate chambers: one equipped with electrochromic windows and another with single pane glass as a control. The results showed improved thermal comfort by up to 50% compared to single pane glass and resulted in energy savings of 19% when the glass was in the tinted state.
2.	Pengcheng Wang, Zhongbing Liu, Xiaoyang Zhang, Mengqi Hu, Ling Zhang, Jianhua Fan	Adaptive dynamic building envelope integrated with phase change material to enhance the heat storage and release efficiency: A state of the art review	(Wang et al., 2023) also conducted a state of the art review on the integration of PCMs into adaptive dynamic building envelopes. The results of the review indicate that PCMs can be used to enhance a building envelope's ability to store and release heat. The study found that organic PCMs and macro encapsulation methods are widely used approaches, while intelligent control systems can influence PCM performance.

Tabel 2.1 Previous Research (Continued)

No	Researcher	Research Title	Conclusion
3.	Ali Raza, Mohamed Hechmi, Qaiser uz Zaman, Marc Azab, Dawood khan	Sustainability assessment, structural performance and challenges of self healing bio mineralized concrete: A systematic review for built environment applications	A study by (Raza et al., 2023) conducted a systematic review of the sustainability aspects, structural performance, and challenges of self healing bio mineralized concrete. The results of the study indicate that the use of bacteria allows the crack healing process to occur without manual intervention, thereby potentially enhancing the sustainability and service life of concrete structures.

CHAPTER III
METHODOLOGY

3.1 Research Method

This study employs a literature review method using a qualitative descriptive approach. This method was used to identify, collect, review, and analyze various previous studies related to the implementation of Smart Materials in support of the Green Building concept. The study focuses on three types of Smart Materials: Electrochromic Glass, Phase Change Materials (PCM), and Self Healing Concrete.

The literature review method was chosen because this study does not conduct experiments or direct testing on the materials but rather analyzes the results of research previously conducted by other researchers. Information obtained from various sources is then compared to determine the characteristics, mechanisms of operation, application examples, benefits, and the contribution of each Smart Material to building efficiency and sustainability.

The analysis was conducted by grouping the research findings based on several aspects, namely energy efficiency, thermal comfort, reduction of environmental impact, building maintenance, material service life, and their potential application in Green Buildings.

3.2 Data Source

The data used in this study consists of secondary data obtained from various scientific sources. The primary sources are journal articles discussing smart materials, green building, building energy efficiency, sustainable construction materials, and adaptive building technologies. The literature sources used include:

1. International journals.
2. National journals.
3. Books and academic literature
4. Standards or guidelines regarding Green Building.
5. Scientific publications relevant to Smart Materials.

Databases that can be used for literature searches include ScienceDirect, SpringerLink, MDPI, IEEE Xplore, Google Scholar, and university journal databases. Priority was given to studies directly related to the use of Smart Materials in buildings and containing information on the performance, benefits, energy efficiency, sustainability, or application of these materials.

3.3 Literature Search and Selection

A systematic literature search was conducted using keywords related to smart materials, green building, energy efficiency, and building sustainability. A search strategy was necessary to ensure that the retrieved literature aligned with the scope of the research and was reliable. In the literature review, the selection process generally involved reviewing titles and abstracts, followed by a review of the full text of potentially relevant articles. The keywords used in the literature search include:

1. Smart Materials and Green Building
2. Smart Materials and Sustainable Building
3. Electrochromic Glass and Energy Efficiency
4. Electrochromic Smart Window and Green Building
5. Phase Change Materials and Building Energy Efficiency

6. PCM and Thermal Comfort
7. Self Healing Concrete, Sustainability Self Healing Concrete and Green Building.

The literature selection process was conducted in several stages: identification, screening, eligibility, and inclusion. The identification stage involved collecting articles based on keywords. Next, articles were screened based on their titles and abstracts. Articles deemed relevant were then reviewed in full to ensure their alignment with the research objectives. This approach is also consistent with the principles of systematic review reporting, which employs a phased selection process. The literature selection procedure was also guided by systematic review principles that involve identification, screening, eligibility assessment, and final inclusion of relevant studies. (Page et al., 2021).

3.4 Research Framework and Procedure

The research framework is used to outline the stages of the research, from problem identification to drawing conclusions regarding the implementation of Smart Materials in support of Green Building.

The study began by identifying problems in conventional buildings, particularly those related to high energy consumption, cooling needs, resource use, building maintenance, and environmental impact. These issues were then linked to the concept of Green Building, which emphasizes energy efficiency, resource efficiency, occupant comfort, and building sustainability.

Next, a study was conducted on three types of Smart Materials: Electrochromic Glass, PCM, and Self Healing Concrete. Each material was analyzed based on its characteristics, operating mechanisms, applications, research findings, and its contribution to building efficiency and sustainability.

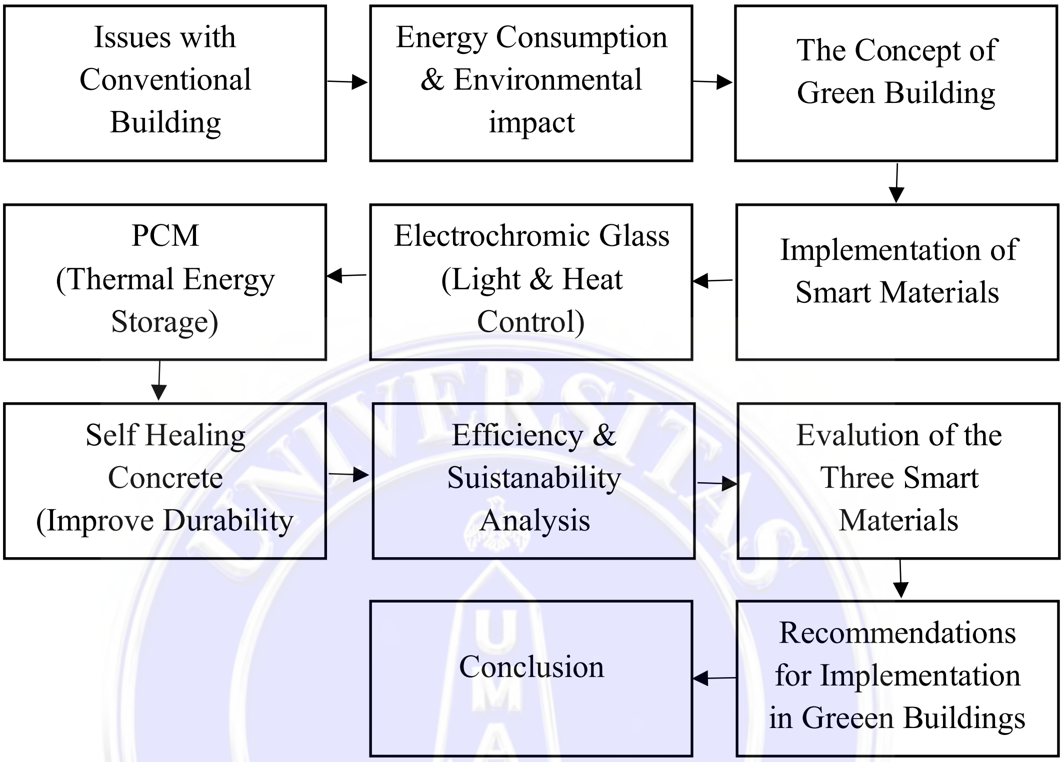

Figure 3. 1 Research Framework

CHAPTER IV

ANALYSIS RESULTS

4.1 The Implementation of Electrochromic Glass in Green Buildings

4.1.1 How Electrochromic Glass Work

Electrochromic glass is a type of smart glass that can change its level of transparency when an electric current is applied. This change in transparency allows buildings to control the amount of light and solar radiation entering a room.

When solar intensity is high, the glass can be darkened to reduce the amount of heat entering the building. Conversely, when solar intensity is low, the glass can be made more transparent to allow natural light to enter the room. The effectiveness of electrochromic windows depends not only on the optical properties of the material but also on building design, climate conditions, façade orientation, and control strategies used in the building system. (Wu et al., 2023).

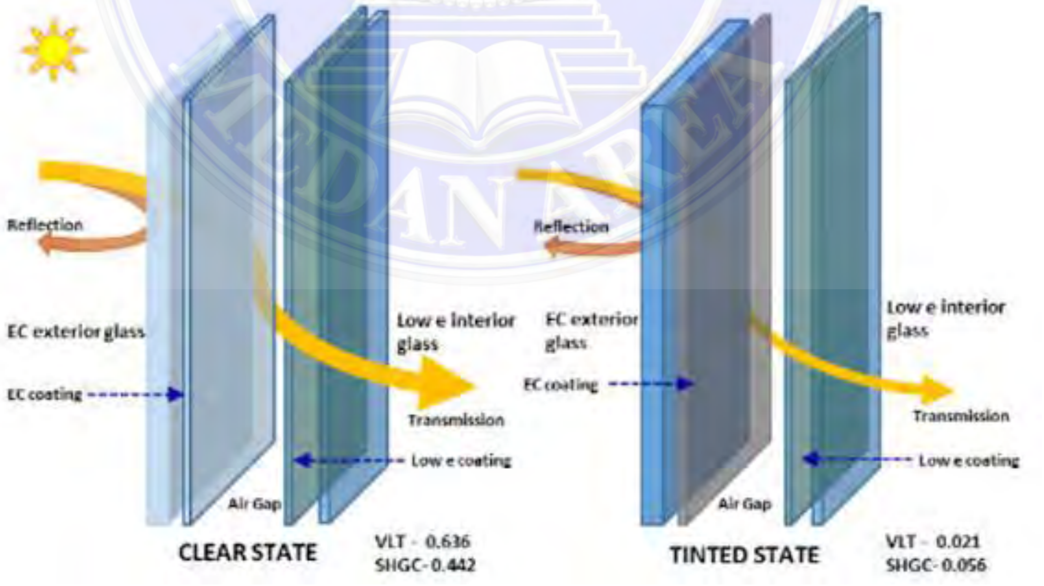

Figure 4. 1 Schematic of an EC Glazing in its clear and dark state

Several studies indicate that the use of electrochromic glass has the potential to reduce a building's energy consumption. A study by (Y. Li et al., 2023) on the use of electrochromic windows in Singapore's tropical climate

The study showed that the glass's ability to regulate light transmission. A study by (Budaiwi & Abdul Fasi, 2023) also showed that electrochromic smart windows can offer potential energy savings in office buildings. However, the material's performance is also influenced by the control system, climatic conditions, building orientation, and users' lighting needs.

4.1.2 Application in Eco Friendly Buildings

Electrochromic glass offers several benefits. Firstly, it allows for dynamic control over the amount of light and heat entering a building, enhancing energy efficiency and reducing reliance on artificial lighting and cooling systems headline advantages summarised in smart glass benefits. Additionally, it provides privacy on demand, as the glass can switch from transparent to opaque with a simple switch or automated control. This feature is particularly useful in office spaces, conference rooms, and residential settings where privacy is desired; for layouts, wiring and controls, use the switchable glass privacy solutions checklist.

The applications of electrochromic glass are vast. It is commonly used in commercial buildings, hotels, hospitals, and residential constructions. It can be integrated into windows, skylights, partitions, and facades, offering architects and designers greater flexibility in creating sustainable and visually appealing spaces.

4.1.3 Advantages and Limitations of Electrochromic Glass

Advantages of Electrochromic Glass:

1. Reduces solar heat gain.
2. Reduces the load on the air conditioner.
3. Optimizes natural lighting.
4. Improves occupant comfort.
5. Can be controlled automatically.

The long term development of smart window technologies also indicates that durability, response time, optical performance, and production costs remain important considerations for wider commercial implementation. (Syrrokostas et al., 2022).

Limitations of Electrochromic Glass:

1. Relatively high investment cost.
2. Control system
3. Requires electricity to operate certain systems.
4. Performance is affected by climate and building orientation.

4.2 The Implementaions of PCM in Greeen Buildings

4.2.1 How PCM Work

Phase change materials (PCMs) are substances that absorb or release a large amount of "latent" heat when they undergo a change in physical state that is, from solid to liquid and vice versa. During heating or cooling, this phase change occurs immediately after the material reaches its specific phase change temperature. During the absorption or release of latent heat, the PCM's temperature remains constant. The ability of PCMs to absorb and release large amounts of heat in a controlled manner can be utilized to improve the thermal performance of various end products that use PCMs. The latent heat absorbed by the PCM can be stored within it. Therefore, PCMs are considered highly efficient thermal storage media.

Phase change materials (PCMs) are theoretically capable of changing states at nearly constant temperatures and can therefore store large amounts of energy to regulate temperature fluctuations. PCMs can exist in at least two distinct phases (an amorphous phase and one or more crystalline phases) and can be repeatedly transformed between these phases.

Phase change materials (PCMs) have a high heat of fusion, allowing them to absorb a great deal of energy before melting or freezing. The temperature of a PCM remains constant during phase changes, which is useful for keeping objects at a uniform temperature. This is one of the applications of technical textiles.

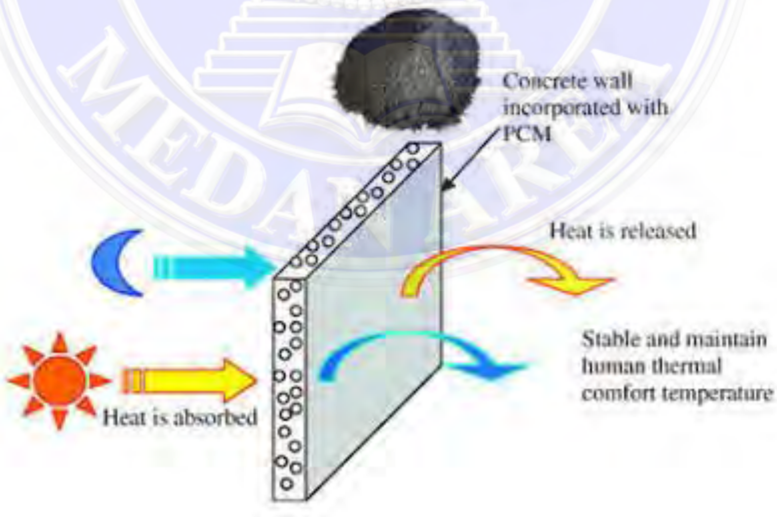

Figure 4. 2 Ilustration How PCM Work

Previous research has shown that Phase Change Materials (PCM) have the potential to maintain temperature stability inside buildings through their ability to absorb, store, and release thermal energy during the phase change process. PCM is incorporated into the building envelope such as walls, ceilings, floors, building panels, and other construction materials. When the ambient temperature rises and reaches the PCM's phase change temperature.

Studies on the integration of PCMs into buildings in hot climates indicate that the use of PCMs has the potential to improve a building's thermal performance and reduce energy demand for cooling. (Zhan et al., 2023), through a study on the integration of PCM into buildings in hot climates, explain that PCM standards can account for PCM types, temperature changes, installation locations, material thickness, climatic conditions, measurements, and building volatility characteristics. Therefore, selecting a phase change temperature that aligns with environmental conditions is a key factor.

PCM can also be applied to building materials such as bricks, wall panels, ceilings, and composite materials. Integrating PCM into these elements allows buildings to have greater heat storage capacity, thereby slowing down temperature changes indoors. When ambient temperatures are high, PCM absorbs some of the heat energy, reducing the amount of heat transferred into the interior space. During periods of lower temperatures, the stored heat can be released gradually. Through this mechanism, PCM can help reduce thermal stress.

Furthermore, (Wang et al., 2023) explain that integrating PCM into buildings can enhance a building's ability to store and release thermal energy. Such integration is becoming increasingly important for buildings.

Based on the results of previous studies, it can be concluded that PCM contributes to the concept of Green Building, particularly in terms of energy efficiency and thermal comfort. PCM does not directly result in energy savings like mechanical devices do.

4.2.2 Application in Eco Friendly Buidings

Phase Change Materials (PCM) can be applied to various building components, such as walls, ceilings, floors, building panels, bricks, and even the entire building envelope. In addition to walls and ceilings, PCM can also be integrated into window systems to dynamically regulate heat transfer between indoor and outdoor environments. (C. Li & Tang, 2024). PCM can also be incorporated into cement based materials and concrete elements to improve thermal energy storage capacity and contribute to more sustainable building envelopes. (Osibodu et al., 2024). The use of PCM significantly contributes to Energy Efficiency due to its ability to absorb, store, and release latent heat during phase changes (for example, from solid to liquid or vice versa). This thermal storage characteristic stabilizes indoor temperatures, preventing external heat fluctuations from directly entering the building. As a result, the workload on both air conditioning (AC) and heating systems is drastically reduced, which directly and efficiently cuts electricity consumption without requiring additional mechanical energy.

In addition to energy efficiency, the use of PCM greatly supports Indoor Health and Safety for building occupants. By absorbing excess heat during the day and releasing it as nighttime temperatures begin to cool, PCM is able to consistently maintain the indoor air temperature within the thermal comfort range. This stable indoor temperature prevents extreme temperature fluctuations that often cause thermal stress, fatigue, and respiratory problems for the occupants. An indoor environment with a naturally stable and cool temperature also minimizes reliance on artificial air circulation from air conditioning which tends to be dry thereby maintaining healthy air humidity levels and improve indoor environmental quality.

4.2.3 Advantages and Limitations of PCM

The performance of PCM is strongly influenced by factors such as melting temperature, thermal conductivity, material thickness, installation location, solar exposure, and local climatic conditions. (Mohan et al., 2026).

Advantages of PCM:

1. Reduces temperature.
2. Reduces load.
3. Improves comfort.
4. Allows for simultaneous interaction.

Limitations of PCM:

1. The price of some types of PCM is relatively high.
2. Performance is affected by phase change temperatures.
3. Requires proper integration design.
4. Storage capacity may decrease depending on usage conditions.

4.3 The Implementation of Self Healing Concrete in Green Buildings

4.3.1 How Self Healing Concrete Work

Self healing concrete is concrete designed to automatically repair cracks. One widely developed approach involves the use of microorganisms or bacteria that can produce calcium carbonate ($CaCO_3$) to fill the cracks. Self healing concrete represents one of the emerging technologies in sustainable construction because it can improve structural durability and reduce the environmental impacts associated with frequent maintenance and repair activities. (Nilimaa, 2023).

When cracks form and environmental conditions permit, the healing mechanism is activated, allowing the material to reduce the size of or close certain cracks. Previous research has shown that self healing concrete has the potential to improve durability and extend the service life of concrete structures. Unlike conventional concrete, which generally requires manual inspection and repair when cracks occur, self healing concrete is designed with specific mechanisms that allow the material to heal itself. This capability can reduce the need for human intervention regarding small cracks and help maintain the concrete's condition over a longer period. With reduced repair frequency, the use of this material also has the potential to reduce the consumption of additives, maintenance costs, and waste generated during a building's service life.

One widely developed technology is bacteria based self healing concrete concrete that utilizes the activity of microorganisms or bacteria to produce mineral products capable of filling cracks. Under certain conditions, bacteria present in the concrete can become active when air or moisture enters through cracks. The bacteria's metabolic activity then produces compounds that trigger the process of biomineralization, particularly the formation of calcium carbonate ($CaCO_3$). These calcium carbonate deposits gradually fill the voids in the cracks, causing the crack width to narrow or close entirely.

This mechanism is known as a form of autonomous healing, because the healing process does not require direct external intervention to repair the structure. However, the self healing capability of concrete does not mean that it can automatically repair all types of damage. The effectiveness of the healing process is greatly influenced by crack width, the type of self healing technology, the type of healing agent, humidity levels, temperature, the age of the concrete, and environmental conditions. In general, this technology is more effective for small or micro cracks, whereas larger cracks or severe structural damage still require conventional repair methods.

Figure 4. 3 How Self Healing Concrete Work

One key parameter in evaluating Self Healing Concrete is crack closure that is, the extent to which the crack is successfully closed following the healing process. For example, if an initial crack has a certain width and that width decreases after the self healing process, it can be said that closure has occurred. However, visual crack closure does not always mean that all of the concrete’s mechanical properties have returned to their initial state. Therefore, research on self healing concrete typically examines not only crack closure but also the recovery of strength, permeability, airtightness, and durability.

4.3.2 Application in Eco Friendly Buildings

The application of Self Healing Concrete can be implemented across various infrastructure elements, including building structures, basements, bridges, hard to maintain concrete elements, and building components that demand high durability. By incorporating autonomous repair mechanisms such as bacterial agents or microencapsulated healing materials that seal cracks upon exposure to moisture and air, this innovative material directly supports the principles of Material Resources and Cycle. It significantly lowers the demand for raw materials typically needed for ongoing structural repairs and maintenance. Furthermore, by extending the overall service life of the building, self healing concrete reduces resource consumption and minimizes the solid waste generated throughout the entire lifecycle of the structure, fostering a far more sustainable and circular construction ecosystem.

4.3.3 Advantages and Limitations of Self Healing Concrete

Advantages of Self Healing Concrete:

1. Capable of repairing certain types of cracks.
2. Improves durability.
3. Reduces the frequency of maintenance.
4. Has the potential to extend service life.
5. Reduces the use of repair materials.

Limitations of Self Healing Concrete:

1. Relatively high material costs.
2. Not all types of cracks can be repaired.
3. Effectiveness is influenced by environmental conditions.

4. The technology still requires further development.

4.4 Contribution of Smart Materials to Green Building Efficiency

Smart materials integrated into building envelopes can provide adaptive responses to environmental changes, contributing simultaneously to energy efficiency, occupant comfort, and reduced environmental impact. (Barbhuiya et al., 2025). The implementation of smart materials plays a pivotal role in optimizing building performance and advancing sustainable architecture across four key dimensions:

1. Energy Efficiency

   Smart materials such as electrochromic glass and Phase Change Materials (PCMs) provide dynamic thermal and optical control over the building envelope. Electrochromic glass features an electronically alterable tint that actively regulates solar heat gain coefficient (SHGC) and visible light transmittance (VLT) in response to real time ambient sunlight. Simultaneously, PCMs utilize latent heat storage to absorb excess heat during peak solar hours and release it when temperatures drop. When integrated, these technologies level off peak indoor temperature spikes and drastically lower the operational load on Heating, Ventilation, and Air Conditioning (HVAC) systems, resulting in substantial electricity savings. Smart materials applied to building façades can significantly influence energy performance by regulating heat transfer, solar radiation, and daylight entering the building. (Fathi & Fakhraeimanesh, 2025).

2. Resource Efficiency

   Self healing concrete incorporates bio based agents or microencapsulating chemical precursors that autonomously seal micro cracks upon contact with moisture and oxygen. By neutralizing structural degradation before cracks propagate, this material minimizes the frequency and scale of conventional maintenance interventions. Consequently, it slashes the demand for fresh raw materials such as cement and aggregate and drastically extends the service lifespan of structural assets.

3. Occupant Comfort and Well being

   By stabilizing both visual and thermal environments, smart materials significantly enhance indoor environmental quality (IEQ). Electrochromic glass suppresses glare while maintaining direct access to natural daylight and external views, reducing visually stressful conditions and eye strain. Concurrently, PCMs prevent rapid interior temperature fluctuations, maintaining a steady, comfortable indoor thermal state that optimizes human health, well being, and productivity.

4. Environmental Impact Reduction

   The combined application of smart materials drives significant decarbonization throughout the building life cycle. On the operational front, reduced HVAC electricity consumption leads directly to a lower carbon footprint in energy production. On the embodied front, extending structural durability through self healing technologies conserves virgin natural resources and substantially decreases demolition, replacement, and construction waste diverted to landfills.

4.5 Challenges in Implementing Smart Materials

Despite their great potential, the application of smart materials in green buildings still faces several challenges.

1. Investment Costs

   Most smart materials have higher upfront costs than conventional materials. Therefore, an evaluation should not be based solely on upfront costs but must also consider life cycle costs.

2. Technological Limitations

   Some technologies are still in the development stage and have not yet been widely adopted in commercial buildings.

3. Climatic Conditions

   The performance of materials such as electrochromic glass and PCM is greatly influenced by climatic conditions, building orientation, solar radiation intensity, and ambient temperature.

4. Experts

   The implementation of smart materials requires professionals who understand the characteristics of the materials, control systems, installation, and maintenance.

5. Integration with Building Systems

   Smart materials need to be integrated with other building systems, such as HVAC, sensors, lighting systems, and building management systems, in order to maximize their benefits.

CHAPTER V

CONCLUSION

Based on the literature review and discussion regarding the implementation of Smart Materials in supporting efficient and sustainable Green Buildings, it can be concluded that smart materials have significant potential to improve building performance in terms of energy efficiency, resource efficiency, occupant comfort, and environmental sustainability. The three materials discussed in this study, namely Electrochromic Glass, Phase Change Materials (PCM), and Self Healing Concrete, have different functions but complement each other in supporting sustainable building principles. Electrochromic Glass can dynamically regulate solar radiation and natural light entering the building, thereby reducing heat gain and potentially lowering the energy required for cooling while maintaining visual comfort.

Phase Change Materials (PCM) contribute to building energy efficiency through their ability to absorb, store, and release thermal energy during phase changes. The application of PCM in building envelope elements such as walls, ceilings, floors, and panels can help stabilize indoor temperatures, reduce temperature fluctuations, and decrease the cooling load of HVAC systems. In addition, stable indoor temperatures can improve thermal comfort and indoor environmental quality for occupants. However, the effectiveness of PCM depends on factors such as phase change temperature, building design, and environmental conditions.

Meanwhile, Self Healing Concrete primarily contributes to sustainability through improved durability and extended structural service life. Its ability to autonomously seal certain small or micro cracks can reduce the frequency of maintenance and the need for additional repair materials. In particular, bacteria based Self Healing Concrete can utilize biomineralization processes to form calcium carbonate ($CaCO_3$), which helps fill cracks. Nevertheless, this technology cannot repair all types of structural damage and its effectiveness is influenced by crack width, healing mechanism, humidity, temperature, concrete age, and environmental conditions.

Overall, the implementation of Smart Materials can support the principles of Green Building through four major contributions: energy efficiency, resource efficiency, occupant comfort and well being, and environmental impact reduction. Electrochromic Glass and PCM primarily contribute to reducing operational energy consumption, while Self Healing Concrete contributes more strongly to material efficiency, durability, and reduction of maintenance related waste. The combined application of these materials therefore has the potential to improve building performance throughout its life cycle.

However, the implementation of Smart Materials still faces several challenges, including relatively high initial investment costs, technological limitations, dependence on climatic conditions, the need for skilled professionals, and the requirement for integration with other building systems such as HVAC, sensors, lighting, and building management systems. Therefore, the selection and implementation of smart materials should not be based solely on their initial cost or technological advantages, but should also consider life cycle costs, building characteristics, local climate, maintenance requirements, and long term environmental benefits.

The continued growth of the building sector and its contribution to global energy consumption and carbon emissions demonstrate the importance of accelerating the adoption of energy efficient and sustainable building technologies, including advanced smart materials. (Report, 2026). Thus, smart materials can serve as an effective technological strategy to support the implementation of green buildings that are more efficient, comfortable, durable, and sustainable; however, their application must be tailored to the materials' functions, the building's characteristics, environmental conditions, and user needs.

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