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Recent Improvements in Sustainable Architecture and BuildingMaterials for Climate Resilient Infrastructure: A Review

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Abstract

This paper presents a review of recent studies focused on sustainable architecture and building materials for climate-resilient infrastructure. Various aspects of sustainable architecture and construction, including green building materials like UHPC, passive design strategies, and energy-efficient systems have been covered in this review. Many of the studies reviewed explore the use of natural ingredients or waste materials to produce ultra-high-performance concrete as a sustainable alternative to traditional building materials, highlighting its low carbon footprint and high strength-to-weight ratio. Several of the reviewed studies focus on passive design strategies, likenatural ventilation, shading devices, and daylighting, to reduce energy consumption and improve thermal comfort in buildings. One of these studies evaluates the effectiveness of such strategies in a tropical climate, while another explores their potential for retrofitting existing buildings. One study examines the potential for integrating these systems in a net-zero energy building. Overall, the reviewed studies demonstrate the importance of sustainable architecture and building materials in creating climate-resilient infrastructure. They highlight the potential for reducing greenhouse gas emissions, improving energy efficiency, and enhancing occupant comfort and well-being through the adoption of sustainable building practices. The findings of this review will provide insights into sustainable building practices that can inform policy decisions and guide the development of future climate- resilient infrastructure.

Keywords: *Sustainable Architecture, Green Building Materials, Energy Efficient Building, Climate Resilient Infrastructure, Ultra High-Performance Concrete*

1 Introduction

Over the past few years, the need to confront the pressing issues brought about by climate change has become more and more apparent. One particular area demanding immediate action is the built environment, which not only contributes substantially to global greenhouse gas emissions but also remains susceptible to the repercussions of a shifting climate (Aye and Jayalath 2018). In this context, the adoption of sustainable architecture and the advancement of climate-resilient building materials have emerged as promising approaches to alleviate environmental burdens and fortify infrastructure resilience.(Yang, Yu, Shui, Gao, Han, et al., 2020) The paper aims to provide an overview of the latest advancements in sustainable architectural practices and innovative building materials that contribute to climate resilience. By synthesizing existing research, this review paper seeks to highlight the key trends, challenges, and opportunities in this evolving field, including their limitations.

The first section of the paper will delve into the concept of sustainable architecture, emphasizing the integration of energy-efficient design, passive strategies, and renewable energy systems (Chaturvedi, et al. 2018). It will explore how sustainable architectural practices can minimize energy consumption, reduce greenhouse gas emissions, and optimize the overall performance of buildings in different climatic regions (Nocentini, Biwole and Achard 2018). Additionally, the section will touch upon the importance of considering life cycle assessment, occupant comfort, and well-being in sustainable architectural design.

The second section will focus on advancements in building materials, basically concrete, that promote climate resilience. It will explore the development and implementation of eco-friendly and high-performance concrete using different waste materials, such as recycled and biodegradable materials and low-carbon concrete(Hamada et al., 2023) (Islam & Rahman Khan, 2021). The paper will also highlight the importance of interdisciplinary collaboration among architects, engineers, policymakers, and researchers to drive sustainable practices in the construction industry.

Overall, this review paper aims to provide a comprehensive understanding of recent improvements in sustainable architecture and building materials for climate resilient infrastructure. By shedding light on the latest advancements, challenges, and opportunities, this paper intends to inspire further research and promote the adoption of sustainable practices that can contribute to a more resilient and environmentally responsible built environment.

2 Passive And Low Energy Buildings

Passive and low-energy buildings are where special design criteria is in place to reduce the operational energy consumption in a building. They are designed to provide a significant reduction of the energy need for building's ecological footprint and to improve Heating, Ventilation, and Air-Conditioning (HVAC) systems, lighting, building envelope elements etc. which depends on Passive solar design, High levels of insulation, Good air tightness standards, Controlled ventilation, High performance glazing and Efficient heating systems (Chaturvedi,et al. 2018). Building envelope is a prime component in building structure and separates the indoor and outdoor environment and reduces the heat transfer (Aye and Jayalath 2018). Lightweight cement with lower material density, lower thermal conductivity and autoclave aerated concrete with inherent nature of high porosity of AAC results in superior thermal properties, which reduces heating and cooling load in the building envelope(Teng et al.,2023). Roof is susceptible for solar radiation so it affects the indoor occupant comfort as well as the outdoor air temperature in urban areas it accounts for 20%–25% of total urban surfaces (Aye and Jayalath 2018). In recent days, Some passive techniques have been used to reduce the solar absorptivity of the roof, which includes solar reflective/cool roofs, green roofs either partly or fully covered with vegetation, roof insulation, evaporative roofs,and photovoltaic (PV) roofs. Gypsum plaster wallboards with embedded PCM has been used to reduce peak indoor temperature recently (Aye and Jayalath 2018). The earth to air exchangers directly use for space heating and cooling in buildings . the air temperature at the outlet, geological properties of the soil, pipe characteristics relatedto heat exchange and site climatic conditions are the factors of affecting the effectiveness of ground cooling systems. It reduces the electricity consumption of a typical building by 25%–30%. Cold night air is also used cooling down the heat absorbed by the building. Reduce daytime temperature increase(Nandanwar, 2015).
The performance of these passive methodologies is highly dependent on the climatic conditions, thus an appropriate design strategy needs to be used with proper understanding on climatic factors.(Gao & Meguid, 2018)

3 Advances in Energy-Efficient Buildings for New and Old Buildings

Population growth and rising energy demand have both led to major increases in energy usage. Currently, buildingsaccount for more than 40% of world energy use and 33% of global GHG emissions (Chaturvedi, et al. 2018).
Numerous studies have demonstrated that EEBs present prospects for financial savings while also lowering GHGemissions.
Building automation, which is a recent addition to the construction industry, can improve occupant comfort, the efficiency of building systems, and to reduce energy consumption and operating costs(Siekmeier, 2018). Automation has been achieved by various means including mechanical, hydraulic, pneumatic, electrical, electronic devices and computers, usually in combination known as Smart Building Automation System (SBAS) (Chaturvedi, et al. 2018). Unlike automation, energy efficient and eco-friendly materials installation is not an easy task in old or constructed buildings. It is wiser to implement these materials in design and construction phase. Energy efficient materials areaffordable and more efficient (Nocentini, Biwole and Achard 2018).

4 Silica Aerogel Blankets as Super-Insulating Material for Developing Energy Efficient Buildings

A new kind of insulation called Super-Insulation material with a thermal conductivity lower than that of air (25 mW.m-1.K-1).However, their manufacturing cost remains high, so the latest research efforts are focused on the reduction of time and cost in the manufacturing process of such Super-Insulating materials such as Silica Aerogel(Nocentini, Biwole and Achard 2018).

However, Several SA has some drawbacks such as Silica skeletons are fragile, rise in heat flow as temperature rises, the process of supercritical drying takes time. Due to these drawbacks, further study is being done on how to create an effective Silica Aerogel substitute. Thus, the study analyzes the production process and effectiveness ofSilica Aerogel over Aerogel Blanket (Nocentini, Biwole and Achard 2018).
As Aerogel blankets are highly porous materials, and water vapor can pass through the pores. So, a factor "The water vapor diffusion resistance μ" was chosen as the main parameter for this study. It indicates the relative magnitude of the water vapor resistance of the product and that of an equally thick layer of stationary air at the same temperature. Here the μ value for the Aerogel blanket remained between 5.5- 8.2. It is acceptable for a thermalinsulating material. Typical mineral wools have μ = 1–3, and organic insulations have μ = 60–150.

Table 1. Basic Properties of Aerogel Blankets (Nocentini, Biwole and Achard 2018)

Basic Properties of the Aerogel Blankets

	Native Silica Aerogel	Needle Glass Fibers Wool	NGF Aerogel Blanket
Length (side) (mm)	Granular	150	150
Thickness (mm)	X	6	8
Volume fraction of fibers	X	4%	4%
Thermal conductivity ($mW.m^{-1}.K^{-1}$)	14–15	31	15–17
Density ($g.cm^{-3}$)	100–110	100	150
Flexural strength (kPa)	<20	X	206.6

Although residential structures still have the majority of potential. With less thickness, it can provide the same insulation as traditional insulating materials (Nocentini, Biwole and Achard 2018). In the future, aerogel blanketsmight be a worthy replacement for traditional insulation.
Although the concept is currently uncommon in underdeveloped nations like Bangladesh, interest in GB (Green Building) is growing. Buildings in Bangladesh that are both commercial and residential use close to 32% primaryenergy (Nocentini, Biwole and Achard 2018).

5 Ultra-High Performance Concrete (UHPC)

Ultra-high-performance concrete (UHPC) is a material that has gained significant attention in recent years due to its exceptional mechanical properties, durability, and potential for sustainable construction(Du et al., 2022). However, the high production costs and environmental impact of UHPC have limited its widespread use in construction applications(Hamada et al., 2023; Shi et al., 2021). The use of secondary aggregate in UHPC can be ecofriendly by reducing the waste that goes into landfills and reducing carbon emissions associated with the production of cement, which is responsible for about 8% of global carbon emissions, and can improve the overall performance of UHPC, particularly in terms of durability and sustainability as well(Wang et al., 2019). Recycled materials can improve the microstructure of UHPC by reducing the porosity and improving the packing density ofthe particles(Wang et al., 2019). Furthermore, the use of recycled materials can improve the long-term sustainability of UHPC by reducing the need for virgin materials and conserving natural resources(Yu et al., 2021). Despite the potential benefits of using secondary aggregate in UHPC, there are some challenges that need to be addressed. One of the main challenges is the variability of recycled materials(Islam & Rahman Khan, 2021). Therefore, it is important to carefully select and test recycled materials to ensure their suitability for UHPC production(Yang et al., 2019). It has been found that the UHPC with EGA had better comparable mechanical properties to conventional UHPC and other secondary aggregates, with a compressive strength of over 127 MPa and a flexural strength of over 21 MPa(Ghafari et al., 2015; Xu et al., 2023). Additionally, the water absorption of UHPC with EGA was lower than that of conventional UHPC, indicating better durability and resistance to moisture. The life-cycle assessment (LCA) of UHPC with EGA also shows distinguishable results from other secondary aggregates, showing a significant reduction in environmental impact compared to conventional UHPC.

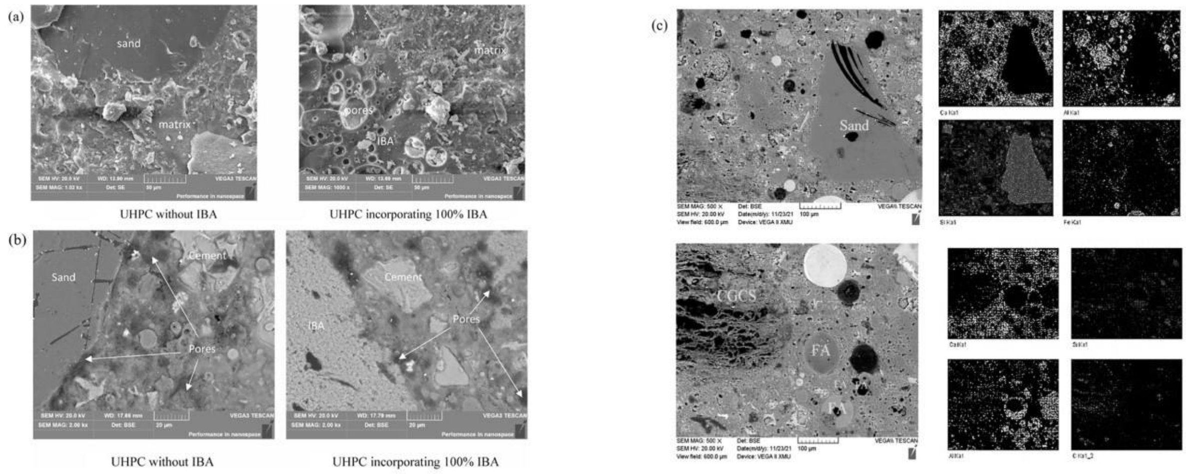

Fig 1. SEM images interfacial transition zone (ITZ) between the cement matrix and aggregates of UHPC with IBA (incineration bottom ash) (b and c) and coal gasification coarse slag (CGCS) (reproduced under Creative Commons license from Zhu et al., 2022; reproduced under license number 5490570762067 from Shen et al., 2020a)

The embodied carbon footprint of UHPC with EGA was approximately 16% lower than that of conventional UHPC. Additionally, the designed UHPC with 15% micro-coral sand and 30% coral sand together showed the comparable properties(Teng et al., 2023; Yang, Yu, Shui, Gao, Han, et al., 2020; Yang, Yu, Shui, Gao, Xiao, et al., 2020). The use of secondary aggregate in UHPC has the potential to address the environmental and economic challenges associated with UHPC production while improving the performance and durability of the material. However, careful consideration of the quality and availability of recycled materials is necessary to ensure the suitability of UHPC for specific applications. Figure 2. shows a comprehensive analysis of UHPC in accordance with embedded CO_2, compressive strength, and replacement level different waste materials.

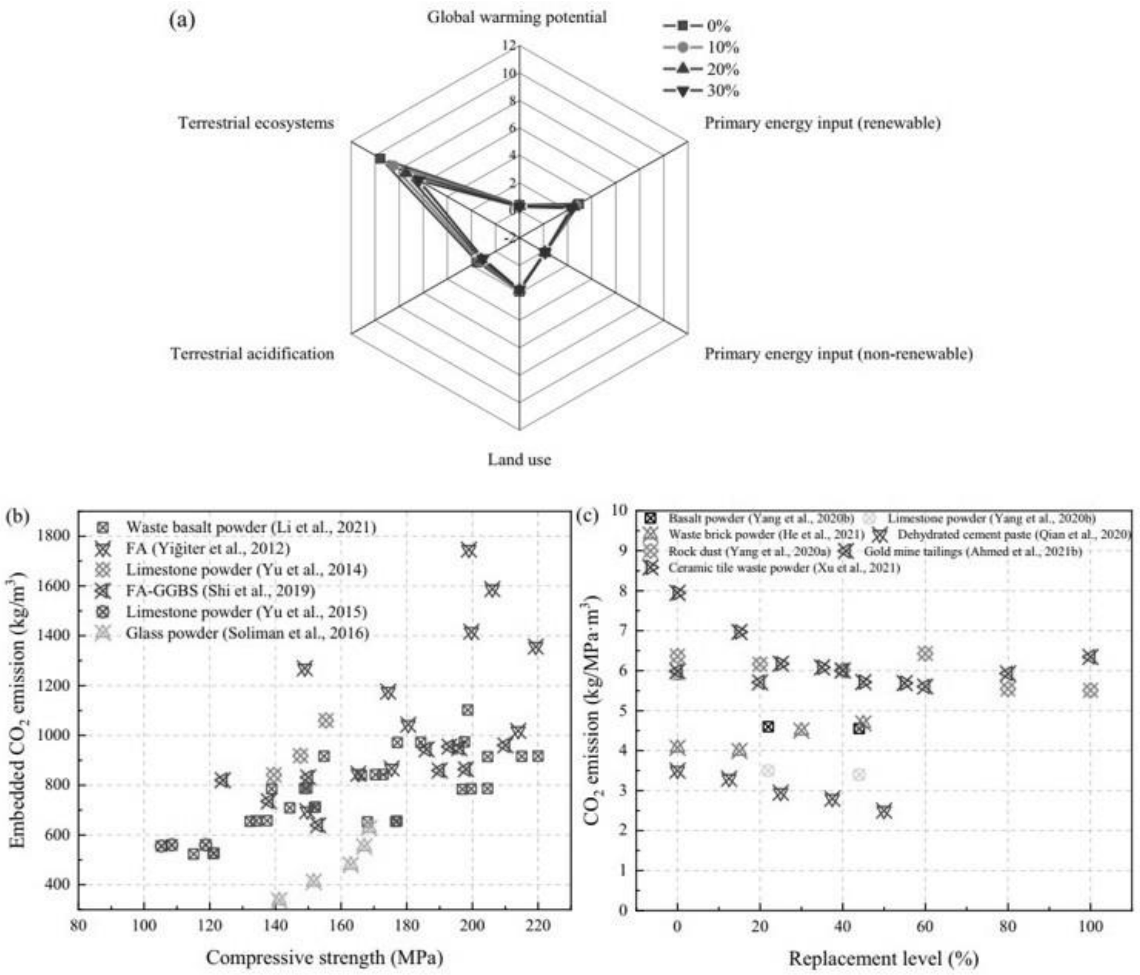

Figure 2. Environmental benefit (a) and CO2 emission (b and c) of UHPC with solid waste(Hamada et al., 2023)(Fan et al., 2021)(Yu et al., 2015)(Wang et al., 2017)(Randl et al., 2014)(Li et al., 2019)(Yang, Yu, Shui, Gao, Han, et al., 2020)(Teng et al., 2023)(Shi et al., 2021a)(Yang, Yu, Shui, Gao, Xiao, et al., 2020)(Du et al., 2023)(Xu et al., 2023)(Ghafari et al., 2015)(Yang et al., 2019) (Yu et al., 2021) (Du et al., 2022a) (Wang et al., 2019) (Shi et al., 2021b)(Du et al., 2022b) (Yang, Yu, Shui, Gao, Han, et al., 2020)(Teng et al., 2023)(Shi et al., 2021a)(Yang, Yu, Shui, Gao, Xiao, et al., 2020)

Future research should focus on developing standardized testing protocols for recycled materials and investigating the long-term performance and durability of UHPC with secondary aggregate(Fan et al., 2021; Guo et al., 2023; Wang et al., 2017; Yu et al., 2015). This review highlights the challenges and comparison between different secondary aggregates in UHPC. Overall, the review presents a comprehensive analysis of the sustainability and performance of UHPC using secondary aggregate, providing valuable information for researchers, engineers, andpractitioners in the field of sustainable concrete technology.

6 Conclusions

Using an appropriate amount of solid waste to replace traditional aggregates is beneficial to improve the performance of UHPC, which benefits from the rough surface and water storage capacity of aggregates. The use of secondary aggregate in UHPC has the potential to address the environmental and economic challenges associated with UHPC production while improving the performance and durability of the material. The replacement level of solid waste was 10% - 30%, the global warming potential value was reduced by 10.8% - 32.5%. So, this could be the potential procedure for the future concrete industry. Careful consideration of the quality and availability of recycled materials is necessary to ensure the suitability of UHPC for specific applications. Future research should focus on developing standardized testing protocols for recycled materials andinvestigating the long-term performance and durability of UHPC with secondary aggregate. The integration of energy-efficient design, passive strategies, and renewable energy systems in sustainable architectural practices can significantly reduce energy consumption and greenhouse gas emissions, while optimizing building performance indiverse climatic regions. The advancement of eco-friendly building materials, such as recycled and biodegradable options, low-carbon concrete, and advanced insulation systems, contributes to climate resilience by minimizing environmental impacts and enhancing durability. However, the negative side of these advance applications, like greenhouse gas emission while producing UHPC, should be taken into consideration as well.

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