DEVELOPMENT OF LIGHTWEIGHT FOAM CONCRETE PANELS WITH HIGH AMOUNT OF CONSTRUCTION AND DEMOLITION WASTE

YÜKSEK HACİMDE İNŞAAT VE YIKINTI ATIĞI İÇEREN HAFİF KÖPÜK BETON PANELLERİN GELİŞTİRİLMESİ

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ABSTRACT

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The construction sector faces significant sustainability challenges due to its high resource consumption, CO2 emissions, and the environmental impact of building insulation practices. Portland cement, a key industry component, is a major contributor to CO2 emissions, necessitating greener practices to align with global sustainability goals. Lightweight foamed concretes, known for their low thermal conductivity and density, are gaining importance in insulation applications, but their reliance on Portland cement and aggregates raises sustainability concerns. To address this, the use of construction and demolition waste (CDW) as substitutes or binders in building materials is being explored. CDW can reduce the carbon footprint of cement production and improve building energy efficiency, promoting a circular economy in the construction sector.

This study focuses on developing non-structural, lightweight building insulation materials using a significant amount of CDW. An eco-hybrid cement was created as the binder phase, and fine recycled concrete aggregate (FRCA) was used as the aggregate phase. The physical, mechanical, and thermal properties of the mixtures were evaluated by varying the content of eco-hybrid cement, FRCA, foaming agent, silica-aerogel, and the water-binder ratio. The research successfully developed an ultra-lightweight green foam concrete with low dry density and thermal conductivity, making it suitable for insulation applications. The incorporation of CDW in these materials enhances sustainability and reduces the environmental footprint, aligning with global sustainability objectives.

Keywords: Sustainability, Portland Cement, Lightweight Foam Concrete, Construction and Demolition Wastes, Thermal Properties, Mechanical Properties

ÖZET

YÜKSEK HACİMDE İNŞAAT VE YIKINTI ATIĞI İÇEREN HAFİF KÖPÜK BETON PANELLERİN GELİŞTİRİLMESİ

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İnşaat sektörü, yüksek kaynak tüketimi, CO2 emisyonları ve bina yalıtım uygulamalarının çevresel etkileri nedeniyle önemli sürdürülebilirlik sorunlarıyla karşı karşıyadır. Sektörün önemli bir bileşeni olan Portland çimentosu, CO2 emisyonlarına önemli bir katkıda bulunmakta ve küresel sürdürülebilirlik hedeflerine uyum sağlamak için daha çevreci uygulamalar gerektirmektedir. Düşük ısı iletkenliği ve yoğunluğu ile bilinen hafif köpüklü betonlar yalıtım uygulamalarında önem kazanmaktadır, ancak Portland çimentosu ve agregalara olan bağımlılıkları sürdürülebilirlik endişelerini artırmaktadır. Bunu ele almak için, inşaat ve yıkım atıklarının (CDW) yapı malzemelerinde ikame veya bağlayıcı olarak kullanımı araştırılmaktadır. CDW, çimento üretiminin karbon ayak izini azaltabilir ve bina enerji verimliliğini artırarak inşaat sektöründe döngüsel bir ekonomiyi teşvik edebilir.

Bu çalışma, önemli miktarda CDW kullanarak yapısal olmayan, hafif yapı yalıtım malzemeleri geliştirmeye odaklanmaktadır. Bağlayıcı faz olarak eko-hibrit bir çimento oluşturulmuş ve agrega fazı olarak ince geri dönüştürülmüş beton agregası (FRCA) kullanılmıştır. Karışımların fiziksel, mekanik ve termal özellikleri, eko-hibrit çimento, FRCA, köpürtücü ajan, silika-aerojel içeriği ve su-bağlayıcı oranı değiştirilerek değerlendirilmiştir. Araştırma, düşük kuru yoğunluğa ve termal iletkenliğe sahip ultra hafif yeşil köpük betonu başarılı bir şekilde geliştirerek yalıtım uygulamaları için uygun hale getirmiştir. CDW'nin bu malzemelere dahil edilmesi sürdürülebilirliği artırmakta ve çevresel ayak izini azaltarak küresel sürdürülebilirlik hedefleriyle uyumlu hale getirmektedir.

Anahtar Kelimeler: Sürdürülebilirlik, Portland Çimentosu, Hafif Köpük Beton, İnşaat ve Yıkım Atıkları, Termal Özellikler, Mekanik Özellikler

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SYMBOLS AND ABBREVIATIONS

Symbols

CaO Lime

CO_2 Carbon Dioxide

H_2O_2 Hydrogen Peroxide

Na_2O Sodium oxide

$SOCl_2$ Thionyl chloride

Abbreviations

CDW Construction and Demolition Wastes

CSA Calcium Sulfoaluminate

CW Concrete Waste

EDX Energy Dispersive X-ray Spectroscopy

FITR Fourier Transform Infrared Spectroscopy

FNA Fine Normal Aggregate

FRCA Fine Recycled Concrete Agregate

H2O2 Hydrogen Peroxide

HB Hollow Brick

Micro-CT Micro-computed Tomography

MPC Magnesium Phosphate Cement

OPC Ordinary Portland Cement

RCA Recycled Concrete Aggreagte

RCB Red Clay Brick

RT Roof Tile

SA Silica aerogel

SDG Sustainable Development Goal

SEM Scanning Electron Microscopy

XRF X-ray fluorescence

1. INTRODUCTION

1.1. General

The construction industry is inherently unsustainable due to its intensive consumption of non-renewable resources, high energy use and significant environmental impacts. Cement production, one of the main components of the sector, is estimated to reach 6 billion tonnes annually worldwide [1]. China ranks first in cement production, followed by the USA and India [2]. A major environmental concern is the significant amount of CO_2 emissions associated with cement production [3]. The production of one tonne of cement results in the emission of approximately 0.73 to 0.99 tonnes of CO_2. This significant release of CO_2 occurs mainly during the calcination of limestone ($CaCO_3$), a process that converts lime (CaO) to lime while emitting CO_2 as a by-product [4]. Consequently, the necessity for the construction industry to identify sustainable alternatives and innovative technologies that will minimise the environmental impact of cement production has become increasingly pressing.

Furthermore, the construction industry has generated and continues to generate a considerable amount of construction and demolition waste due to the rapid urbanisation and modernisation of the world. Moreover, these CDW constitute the largest waste streams of solid waste in many countries of the world [5]. In 2014, China generated 1.13 billion tonnes of CDW, accounting for 40% of all waste. Similarly, in 2015, the United States produced 548 megatonnes of CDW, while Europe generated 923.9 megatonnes, representing 34% of all waste in the region [5]. In light of the raising population, economy and developing world, it is evident that CDW management has become one of the significant factors contributing to the generation of waste.

It is anticipated that the contribution of the construction sector to global energy consumption and emissions will continue to increase, taking into account the CO_2 emissions from cement production and the heating and cooling demand of existing buildings, in addition to the significant amount of CDW generated. In the United States, the building sector is responsible for 39% of energy consumption and 38% of CO_2 emissions, while in Europe it accounts for 40% of energy consumption and 36% of CO_2 emissions [6]. In light of this information, the insulation of buildings and the improvement of their energy efficiency become of paramount importance. Lightweight foam concretes with a low thermal conductivity coefficient assume a prominent role in the field of insulation solutions for buildings. Non-structural lightweight foam concrete has a densities from 300 to 1200 kg/m^3, while those used for load-bearing purposes have densities from 1200 to 1600 kg/m^3 [7].

The extant literature indicates that Portland cement remains the dominant binder in the production of lightweight foam concrete. Nevertheless, the utilisation of final recycled and screened fine aggregates derived from the concrete crushing process remains quite limited. This underutilisation is largely attributable to the suboptimal characteristics of recycled aggregates. In contrast to their natural counterparts, recycled aggregates frequently display high water absorption and significant abrasion loss due to the residual cement paste adhering to their surfaces. The aforementioned properties of recycled aggregates result in concrete mixes that exhibit inferior mechanical performance when compared to those made with natural aggregates. In particular, concrete produced with recycled aggregates frequently displays reduced compressive strength, compromised durability, and increased shrinkage. The residual cement paste on the surface of recycled aggregates contributes to their porous nature, which in turn leads to higher water absorption. This, in turn, affects the water/cement and subsequently the workability and strength of the final product.

Notwithstanding the aforementioned challenges, the potential for sustainable utilisation of recycled aggregates in foam concrete should not be overlooked. Incorporation of recycled aggregates into foam concrete aligns with the principles of the circular economy, reducing reliance on virgin materials and minimising CDW. By diverting CDW from landfills and repurposing it into new construction materials, the environmental footprint of the construction industry can be significantly reduced.

The major objective of this thesis is to develop an innovative and sustainable solution that addresses the adverse effects of CDW in the construction sector while reducing the unavoidable emissions from the heating-cooling systems of buildings. By addressing the dual challenges of CDW management and building energy efficiency, this thesis aims to have a transformative impact on the construction industry, promote greener practices and advance the global sustainability target.

The findings of this research are now ready to make a significant contribution to one of the most pressing issues of our time: the management of global warming, CO_2 emissions, and CDWs. To achieve this overarching goal, the following specific objectives have been identified:

- The incorporation of significant quantities of CDW into new construction materials is a key objective of the research, which seeks to establish a circular economy model where waste is repurposed rather than discarded. The development of eco-friendly construction materials involves the formulation of innovative binders and aggregates that can replace traditional Portland cement and natural aggregates. This includes the development of lightweight foam concrete using recycled aggregates, other cement binders, and other sustainable additives.
- The research aims to enhance energy efficiency and reduce the carbon footprint of buildings through the use of advanced thermal insulating materials, such as foam concrete and aerogels. These materials are designed to improve the energy performance of buildings, leading to reduced energy consumption for heating and cooling. By substituting high-energy and CO_2-intensive materials with recycled aggregates and sustainable binders, the research seeks to significantly reduce the carbon footprint of new building materials. The research will concentrate on optimising the performance characteristics of these new materials, ensuring that

they meet or exceed industry standards for strength, durability, and thermal performance.

1.2. Research Objectives and Scope

This thesis is concerned with the development of innovative non-structural ultra-lightweight building insulation materials utilising extensive CDW, including red clay brick (RCB), hollow brick (HB), concrete waste (CW) and roof tile (RT). The utilisation of Eco-hybrid cement, comprising calcium sulfoaluminate (CSA) cement and CDW, as a binder in conjunction with FRCA and silica aerogel, is employed as a means of creating sustainable construction solutions. This approach is designed to significantly reduce the environmental impact and carbon footprint of building materials, thereby providing scalable and commercially viable solutions that align with global sustainability goals.

In this study, a series of experiments were conducted to develop and evaluate an Eco-hybrid cement-based ultra-lightweight foam concrete using FRCA. The process involved preparing a foam mix and a cement-aggregate mortar, which were then combined and poured into moulds for curing. Physical and mechanical properties were tested using methods such as density measurements, flowability tests and compressive and flexural strength assessments. Thermal conductivity was also measured to determine the insulating properties of the material. Microstructural properties were investigated using scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDX) and micro-computed tomography (micro-CT) to analyse the pore structure and composition. The aim of these tests was to optimise the properties of the concrete for environmental efficiency and performance in sustainable building applications.

The green, innovative and applicable objectives that the study aims to reach are listed below:

- This initiative aims to utilise significant amounts of CDW to develop sustainable building materials that not only help reduce landfill waste, but also promote environmental stewardship. By recycling these materials, the thesis contributes to the conservation of natural resources and provides an innovative solution to the management of construction waste, in line with global sustainability practices and reducing the environmental impact of the construction industry.

- This thesis focuses on ensuring that the materials developed are not only technically effective, but also economically viable for widespread adoption. The aim is to create sustainable building materials that can be produced on a large scale without prohibitive costs, thereby encouraging wider industry uptake and integration. By demonstrating the practicality and cost-effectiveness of these innovative materials, the thesis aims to influence construction practices globally and drive the industry towards more sustainable solutions.
- The thesis is strategically designed to support international efforts to reduce environmental impact, directly contribute to reducing carbon emissions and improve energy efficiency in building practices. By aligning with global sustainability goals, such as those discussed in the Paris Agreement and SDGs, the initiative aims to foster a more sustainable construction sector that actively participates in mitigating climate change and promoting environmental stewardship on a global scale.

2. LITERATURE REVIEW

2.1. Lightweight Foam Concrete

Lightweight foam concrete is characterised by the presence of air voids within the cement mortar, which are a consequence of the use of foaming agents. This unique solution offers a variety of construction benefits. With a density ranging from 400 to 1600 kg/m³, this concrete can be employed in several applications, including insulation and structural filling. Its versatility and the significant advantages it offers can be utilised [8]. This type of concrete is distinguished by its excellent fluidity and permeability, which facilitate its application and use in different environments.

Furthermore, lightweight foam concretes are renowned for its exemplary thermal insulation and fire resistance properties, rendering it a preferred option for safety-critical applications. Its minimal self-weight significantly reduces dead loads on structures. These properties are particularly valuable in today's construction environment, where the urgency of global warming and pressure for sustainable practices are paramount [8]. The capacity of lightweight foam concrete to fulfil both environmental concerns and technical construction requirements makes it a progressive choice in the modern building industry [9, 10].

2.1.1. Constituent materials of Lightweight Foam Concrete

The composition of lightweight foam concretes typically comprises four fundamental elements: water, foam, aggregate and binder. In certain studies, alternative materials (such as silica-aereogel, fly ash, ground granulated blast furnace, and so forth) have been employed to enhance the physical, mechanical and thermal properties of lightweight foam concrete [10, 11].

2.1.1.1. Binders

Portland cement is renowned for its versatility and strength and is the most widely used binder in the production of lightweight foam concrete. This cement plays an important role in achieving the desired structural properties of foam concrete, including its durability and compressive strength. Furthermore, the adaptability of Portland cement allows the incorporation of various additives and admixtures that can enhance the performance characteristics of foam concrete. Such materials may include fly ash, silica fume and other pozzolanic materials, which not only help to reduce the environmental impact of concrete, but also improve its workability and long-term strength.

In their study, Zhihau et al. [12] utilised Ordinary Portland Cement (OPC) as the binder. The densities of the lightweight concretes produced varied between 150 and 300 kg/m³ and the 28-day compressive strengths were found to range from 0.33 MPa to 1.1 MPa. One of the key findings of the study was that blast furnace slag had a greater impact on the strength properties of lightweight foam concrete.

In their study, Kearsley and Wainwright [11] replaced up to 75% of the cement with fly ash. They then determined the target density between 1000 kg/m³ and 1500 kg/m³ in the mixtures they designed. The results indicated that the compressive strength of lightweight foam concrete at 28 days and one year was affected by the ratio of cement to fly ash at a very low rate, while this effect was negligible in the long term.

Gökçe et al. [11] conducted a study to investigate the effects of silica fume on the physical and mechanical properties. Their findings revealed that the density of the concrete ranged from 873 kg/m³ to 1998 kg/m³, the strength from 1.5 MPa to 88.1 MPa, and the thermal conductivity from 0.239 W/mK to 0.942 W/mK. It was observed that there was minimal impact on the mechanical and physical properties of lightweight foam concrete when fly ash was substituted for OPC. However, it was found that 20% substitution of silica fume resulted in an increase in density of up to 55%, compressive strength of up to 63.8 MPa and thermal conductivity of up to 37%.

In another study, Şeker et al. [13] employed silica fume as a substitute for OPC. The mixtures were composed of 5% by weight of silica fume. The researchers observed that the lightweight foam concretes produced exhibited densities ranging between 200 kg/m³ and 220 kg/m³, compressive strengths of 0.26 - 0.21 MPa, and conductivity coefficients of 0.073 - 0.069 W/mK. They concluded that silica fume exerts a positive effect on compressive strength, while it affects thermal property at ultimate ages.

The existing literature indicates that the type of cement used can significantly impact various properties of lightweight foam concrete, including strength, thermal conductivity, setting time, flowability, and density. Studies referenced as [12, 14, 15] demonstrate how these characteristics can be tailored to meet specific engineering requirements by altering the cement type.

In their study, Li et al. [16] employed magnesium phosphate cement (MPC) as a binder and hydrogen peroxide (H_2O_2) as a foaming agent in the production of lightweight foamed concrete. The results demonstrated that the density of lightweight foamed concrete produced with MPC ranged between 300 kg/m³ and 1000 kg/m³, with 28-day strengths ranging between 1.8 MPa and 21.6 MPa. Additionally, the thermal conductivity coefficients exhibited a range between 0.136 W/mK and 0.347 W/mK. Another noteworthy outcome is that the strength values of lightweight foamed concrete produced with MPC are considerably higher than those of lightweight foamed concrete produced with normal Portland cement at these density and thermal conductivity values.

Ma and Chen [17] employed MPC as a binder and sodium bicarbonate as a foaming agent. The findings of the studies indicated that while the 3-hour compressive strength was seventy per cent of the compressive strength, the target density was achieved, resulting in a compressive strength of 2.4 MPa and a thermal insulation coefficient value of 0.0072 W/mK.

In a separate study, Yue and Bing [18] reported that lightweight foam concretes using MPC as a binder demonstrated high early strength properties and could be demoulded three hours after pouring. The results indicated that the densities of lightweight foam concretes produced using magnesium phosphate cement ranged between 210 and 380 kg/m^3, with compressive strengths between 1 - 2.8 MPa and thermal conductivities between 0.0049 and 0.07 W/mK. The linear relationship between the amount of cement and density and compressive strength, and the inverse relationship between foam volume and thermal conductivity are noteworthy.

CSA cement represents a contemporary alternative to OPC, distinguished by its high early strength capabilities. This innovative cement type contains a higher proportion of aluminium and a lower amount of calcium oxide compared to OPC. Developed relatively recently, CSA cement offers several advantages, including a faster setting time and greater durability, which render it particularly suitable for specific construction needs where rapid strength gain is desirable [19]. This renders CSA cement a promising material for both industrial applications and infrastructural developments.

In their study, Gołaszewski et al. [20] employed CSA cement in conjunction with OPC and synthetic and protein-based foaming agents to generate specimens with densities spanning from 200 to 500 kg/m^3. Their findings indicated that density exhibited a profound correlation with mechanical properties and thermal properties. Additionally, they demonstrated the protein-based foaming agent facilitated the formation of more stable and regular voids within the hardened mortar matrix. Another noteworthy aspect of the study is that CSA cement enhances the physical, mechanical and thermal properties of lightweight foam concrete, indicating that its incorporation into lightweight foam concrete has considerable potential.

In a separate study, the density of foam concretes produced with CSA cement in combination with OPC was found to be 700–900 kg/m^3. As is commonly reported in the literature, the presence of CSA cement was found to increase the early strength values in this study. The authors supported these findings with the results obtained from 3D XRD analysis. The optimal proportion of CSA cement was determined to be 25% by weight of the total binder [21].

In recent years, geopolymer binders using alkaline activators instead of traditional cements have attracted attention. Geopolymer binders represent a significant advancement in the construction materials industry, particularly because of their environmental benefits compared to traditional cement. Developed more actively in recent years, these binders are noted for their substantially lower carbon emissions [22]. The production of geopolymer binders involves a chemical reaction between aluminosilicate powders and alkali activators, which typically results in a material with excellent mechanical properties and durability. In addition, geopolymers have also found their place in lightweight building materials.

Furthermore, geopolymers have also been identified as a potential solution for the development of lightweight building materials. The study conducted by Zhang et al. [23] demonstrated that geopolymer foam concretes could play a critical role in the advancement of sustainable construction. The researchers reported that the 28-day compressive strengths of geopolymer foam concretes varied between 3 and 48 MPa, with oven-dry densities between 585 and 1370 kg/m3. Furthermore, the thermal insulators exhibited a range of 0.15 to 0.48 W/mK. It is noteworthy that these densities and compressive strengths are comparable to those of lightweight foam concretes produced with OPC.

2.1.1.2.Aggregates

In foam concrete mixtures, the use of coarse aggregate is generally not employed due to the deflation of the foam during mixing, the tendency of the aggregate to settle to the bottom of the mixture due to its high density compared to the mixture, and the disruption of the homogeneity of the matrix [24]. However, the use of fine aggregates is a common practice in the literature and in practice.

The study by Lim et al. [25] examined the impact of sand gradation on the workability and strength of lightweight foamed concrete. The findings revealed that as the sand gradation becomes finer, the workability of the foamed concrete in the fresh state declines, necessitating an increase in the water/binder ratio. Additionally, the specimens produced with the finest sand (0.6 mm) exhibited the highest mechanical properties.

In addition to the conventional using of the fine aggregates in foam concrete, there is a growing body of research exploring the incorporation of lightweight aggregates into these mixtures. These studies aim to further enhance the properties of foam concrete, such as its thermal insulation, structural strength, and overall durability. Lightweight aggregates, which can include materials such as expanded clay, perlite and pumice contribute to reducing the overall weight of the concrete while potentially improving its insulative and fire-resistant properties [25-27]. The utilisation of such aggregates is particularly advantageous in applications that necessitate ease of handling and reduced structural loads. This innovative approach constitutes a component of a broader initiative to optimise construction materials with a view to enhancing efficiency and environmental sustainability.

The objective of the study was to aim to the physical, mechanical and thermal conductivity properties of pumice types extracted from different locations using a 250 kg/m³ cement dosage, a 250 kg/m³ aggregate dosage, a constant target density and a 0.45 w/b ratio. The study employed pumice as a means of compensating for the absence of coarse aggregate in the foam concrete mix. The study yielded two significant findings. Firstly, pumice can be employed as a coarse aggregate in foam concrete. Secondly, the type of pumice has a intricate impact on the physical, mechanical and thermal characteristics of foam concrete [28].

A related study focused on the formulation of foam concrete and employed expanded perlite and fine-sized waste glass sand as aggregates, maintaining a constant water-to-binder (w/b) ratio of 0.5. This study yielded two significant findings, each highlighting the impact of the different aggregates on the properties of foam concrete. It was initially observed that the physical, mechanical, and durability characteristics of the foam concrete exhibited an improvement as the addition of glass sand increased. This improvement is attributed to the low porosity and denser structure provided by the glass sand. The second key finding of the study is the reduction in thermal conductivity observed with the increased addition of perlite. This effect is due to the inherently porous nature of expanded perlite, which contributes to the insulation properties of the concrete. Perlite's structure contains numerous tiny air-filled cavities, which effectively trap air and reduce heat transfer through the material, thereby lowering the thermal conductivity. The results demonstrate the dual benefits of using these specific aggregates in foam concrete: waste glass sand for improving strength and durability and expanded perlite for enhancing thermal insulation [26].

The global phenomenon of climate change and the concomitant rise in public awareness of environmental issues have elevated the issue of concrete recycling to a position of prominence on the international environmental agenda. The recycling of concrete materials serves to conserve natural resources by reducing the demand for virgin aggregate, which in turn reduces the need for quarrying activities that have been identified as having a significant environmental impact in terms of habitat degradation, dust and noise pollution [29]. The recycled concrete aggregates (RCA) produced by this process can be used in a variety of applications, including road base, new concrete mixes [30-32]. It should be noted that recycled concrete may not always be suitable for high-strength applications. However, ongoing research and technological advances are improving the quality and reliability of recycled concrete materials [31, 33, 34].

In their study, Gencel et al. [35] tested the physical, mechanical and insulation properties of concretes obtained by replacing the aggregate in the foam concrete mix with FRCA with ratios ranging from 0 to 100%. The findings of the study demonstrated that as the ratio of FRCA increased, the porosity and water absorption tendency increased due to the porous structure of FRCA, while the thermal conductivity was negatively affected. Furthermore, the study indicated a reduction in compressive strength.

In a separate study, it was observed that as the substitution of FRCA increased in lightweight foam concrete, the physical and mechanical properties of FRCA deteriorated due to its high porosity and high-water demand properties, while thermal properties exhibited an increase with the addition of FRCA [36].

2.1.1.3.Foaming Agent

This section will examine the studies in the literature on foaming agents used in foam concrete production. As the foaming agent plays a dominant role in foam production and in many properties of foam concrete, such as physical, mechanical, insulation, etc., it is necessary to pay attention to the mix design [24]. The role of foaming agents in the mix is to create air voids in the foam concrete. The two most used types of foaming agents are synthetic-based and protein-based [37-39]. Each offers different advantages and is suitable for different applications, depending on the desired result. Protein-based foaming agents create a more stable void structure within the concrete matrix, which plays an important role in increasing the durability and strength of concrete. However, protein-based foaming agents have some disadvantages, including being more expensive than their counterparts and requiring specific storage conditions. Conversely, synthetic foaming agents are economically accessible despite the economic disadvantage of protein-based foaming agents. They can be used for lower-density foam concrete because they have a higher expansion capability than protein-based foaming agents [38-40]. A literature review revealed that the strengths of foam concretes produced with synthetic foaming agents at elevated water/binder ratios were comparable to those produced with protein-based foaming agents [15]

In their investigation , Sun et al. [41] examined the effects of diverse foaming agents on the characteristics of foamed concrete. Foamed concrete was produced at a density of 600 kg/m³ and the structure and properties were found to be significantly influenced by the type of foaming agent employed. FTIR analysis revealed that the foaming agents were similar. However, the stability and strength of the foam produced with synthetic surfactant were found to be significantly higher than others. This is likely due to the higher density and viscosity of synthetic surfactant foam. The compressive strength of synthetic surfactant foamed concrete was found to be 11% and 43% higher compared to other foamed concretes. Furthermore, the drying shrinkage of synthetic surfactant foamed concrete was found to be 13% and 21% lower than other concretes. Overall, the study concluded that the stability and strength of the foam are significantly dependent on the type of foaming agent used. synthetic surfactant foam also improved the flowability of fresh foamed concrete due to its higher water content and water-reducing properties. After 28 days of curing, synthetic surfactant foamed concrete showed the highest compressive strength and the lowest water absorption. This can be attributed to its good foam structure.

In a recent study, the impact of foaming agents on the properties of foamed concrete was examined. The investigation involved creating multiple foamed concrete specimens using varying amounts of both types of agents, resulting in a range of densities. Findings indicated that protein-based agents provided better foam stability and compressive strength than their synthetic counterparts. Specifically, protein-based foamed concrete achieved higher compressive strength at the highest density tested. Additionally, the type of foaming agent was found to significantly influence the properties of the concrete, with protein-based options showing enhanced strength across all densities tested. It was also noted that protein-based concrete demonstrated less drying shrinkage compared to synthetic-based concrete. A microstructural analysis of the protein-based foamed concrete showed it possessed smaller pores, a limited range of pore sizes, and fewer pore junctions, leading to improved performance. The study further detailed the relationships between foam dosage and dry density, providing valuable insights for achieving specific concrete densities without using numerical specifics. Overall, protein-based foaming agents were shown to offer superior stability, strength, and shrinkage properties compared to synthetic agents [42].

Siva et al. [43] conducted a study on a green foaming agent. The objective was to investigate the use of soapnut fruit as a renewable foaming agent for foam concrete, with the aim of replacing synthetic agents. Two methods were employed to prepare soapnut foam solutions: soaking in water without heating and heating the pericarp to 70-90 °C. The foam obtained from these solutions was evaluated for density and stability. Initially, the soapnut foam caused cement setting problems due to compounds in the soapnut. This was solved by adding alum as an accelerator, which allowed additional ettringite formation and achieved favourable setting. The heated soapnut foam showed marginally better properties than the unheated solution. Furthermore, foam concrete produced using heated soapnut pericarp exhibited higher compressive strength and lower water absorption. Pore size and shape analysis revealed good correlations with density and strength. The study concluded that soapnut pericarp represents a viable green alternative to synthetic foaming agents, producing foam that meets ASTM standards, particularly when heated to 80 °C and used with an alum concentration of 5%.

A study utilising sodium lauryl sulphate as a foaming agent revealed a significant reduction in foam density upon production. This observation highlights the challenges inherent in the fabrication of foam concrete. The authors observed that the dilution of the foaming agent resulted in a further decline in foam density. Additionally, they emphasised the necessity for a meticulous evaluation of the foaming agent content and the application methods in the production of foam concrete [44].

Xiong et al. [45] prepared ultra-stable foams using $SOCl_2$ curing and nano-alumina alteration. The study compared the foam properties made with different modified foaming agents and investigated their effects on the mechanical properties, physical properties and homogeneity of foamed concrete. The findings demonstrated that the incorporation of nano-alumina enhanced the density, stability and viscosity of foams generated with foaming agents. The mechanical properties, physical properties and homogeneity of foamed concrete prepared with foaming agents were enhanced by the addition of nano-alumina.

2.1.1.4. Silica-aerogel

Silica aerogels are nano-structured materials with a high specific surface area, high porosity, very low density, exceptional thermal insulation properties and a high specific surface area. They were first discovered in the 1930s [46]. Due to its low density and superior thermal properties, it is anticipated that this material will be utilised in the construction industry for thermal insulation applications.

In their study, Li et al. [47] observed that the density of foam concrete produced by employing a cement/silica-aerogel 17/1 ratio was 198 kg/m3, while its thermal conductivity was 0.049 W/mK. Furthermore, the study indicated that the physical properties of foam concrete exhibited a positive correlation with the silica-aerogel content.

In a further study, the crystal and microstructural properties of foam concrete produced with silica aerogel (SA) were investigated XRD and SEM. Thermogravimetric/differential scanning calorimetry evaluated its thermal stability, while N2 adsorption-desorption tests and transient plane welding method evaluated its pore volume, surface area and thermal properties. The results showed that the matrix of foam concrete with SA exhibited a silica aerogel content of up to 74%, accompanied by a 48.4% reduction in thermal conductivity relative to conventional foam concrete [48].

In their study, Li et al. [49] investigated the influence of SA)on aerogel foamed concrete, varying the particle size and amount of SA. The silica aerogels were integrated seamlessly into the foam concrete matrix, imparting hydrophobic properties to the material. The inclusion of SA markedly altered the material's characteristics, primarily through its defoamer effect, which is influenced by both the particle size and the amount used. The incorporation of smaller particle sizes and higher concentrations of silica aerogel into the aerogel foam concrete resulted in alterations to its microstructure, hydrophobicity, compressive strength, and thermal insulation properties. These changes enhanced the defoamer effect, with aerogel foam containing a significant proportion of silica aerogel exhibiting the highest hydrophobic angle. The study demonstrated that the mechanical properties, physical properties and thermal properties of aerogel foam concrete were intricately influenced by the content and particle size of the silica aerogel. The research indicated that the particle size and content of SA could be adjusted to optimise the overall performance of aerogel foam concrete, thus broadening its practical applications in aerogel composites.

In their study, Adhikary et al. employed three distinct aggregate types: expanded glass aggregates, SA, and plastic bubbles. They then proceeded to investigate the mechanical properties of these aggregates through the use of SEM, quasi-adiabatic calorimetry, and XRD analysis. The results of this investigation led the researchers to identify four key findings. The first finding was that the substitution of silica aerogel up to 15% caused a decrease of up to 45% in compressive strength. Secondly, increasing silica aerogel substitution resulted in the production of concrete with lower densities. The third and most important finding was that weak bonds were observed between aerogel particles and hardened cement particles, which resulted in low strength. Finally, it was observed that the incorporation of both fly ash and prefabricated plastic bubbles into the concrete mixture resulted in the production of flowable lightweight and ultra-lightweight concrete [50].

In their research, Wu et al. [51] developed a method, designated the equal volume replacement technique, with the objective of enhancing the cost-effectiveness of aerogel foamed concrete. This method involves the substitution of ultra-light silica aerogel for conventional lightweight silica aerogel. The researchers examined the impact of aerogel density on the thermal characteristics, compressive strength, and overall density of the material. The findings indicated that ultra-light aerogel foamed concrete exhibited a notable reduction in both density and thermal conductivity, while maintaining a satisfactory level of compressive strength. When an aerogel volume fraction and a foam fraction optimised for performance were employed, the ultra-light aerogel foamed concrete demonstrated a marked decrease in cost and enhanced thermal properties. These findings demonstrate the efficacy of utilising high-performance aerogels in construction applications to enhance energy efficiency and facilitate the implementation of low-carbon construction solutions.

Rong et al. [52] conducted a study investigating alkali-activated aerogel foam concrete as an energy-efficient building material. The study examined the impacts of fly ash, foam, aerogel, and fibers on the microstructure, mechanical and thermal characteristics of concrete. The findings indicated that substituting cement with fly ash enhanced the concrete's thermal insulation properties, although this was accompanied by a reduction in mechanical strength. The addition of foam and aerogel to the mix further lowered the thermal conductivity, but this was accompanied by a considerable decrease in strength. The incorporation of high levels of aerogel and foam resulted in a notable decrease in thermal conductivity, accompanied by a substantial decline in compressive and flexural strengths.

In their study, Chen et al. [53] examined the impact of SA particle size on the thermal and acoustic properties of geopolymer foam concrete. Four types of SA with varies particle sizes were employed in the study. It was observed that the larger particles (700-4000 μm) exhibited a pronounced effect on acoustic absorption and thermal insulation, resulting in an increase in the total and open porosity of the foam aerogel render. The reduction of thermal conductivity was observed in samples containing particles below 10 μm, while the incorporation of larger particles led to an increase in sound absorption, resulting from the formation of a bridging effect between air voids. The optimal foam aerogel render exhibited a thermal conductivity of 0.133 W/mK, an acoustic absorption coefficient of 0.51, and a density of 715.2 kg/m³. The incorporation of 20% volume of silica aerogel resulted in enhanced hygrothermal performance, characterised by a reduction in water uptake and thermal conductivity following conditioning at varying humidity levels. The study offers valuable insights into the use of different aerogel particle sizes to optimise the performance of foam aerogel rendering, in particular maintaining a low content of SA while enjoying all its advantages.

A rather remarkable study was conducted on a foam concrete structure under negative pressure conditions inside an airtight chamber. This was done to ensure homogeneous dispersion of aoregels into the foam concrete matrix. This study differs from other studies in that it differs from conventional methods in terms of homogeneous placement of aoregels into the foam concrete matrix. Among the results of the study, it is quite remarkable that it has a thermal conductivity value of 50% less than conventional foam concrete. The placement of aoregels in foam concrete using this innovative method did not result in any changes to the structural integrity, compressive strength or density of the foam concrete [54].

2.2. CDW Management

While foam concretes are renowned for their excellent thermal and acoustic insulation properties, they are traditionally composed of materials such as OPC, sand, and gravel, which have significant environmental implications. These materials contribute to the high environmental footprint of construction processes due to the substantial energy consumption and CO_2 emissions involved in their production.

A major environmental concern linked with construction activities is the generation of CDW. This type of waste represents a significant component of global solid waste, with China producing approximately three billion tonnes of CDW annually, and the European Union and the United States collectively generating more than 1.5 billion tonnes [55, 56].

The massive quantities of CDW necessitate the implementation of effective waste management strategies to mitigate their impact on landfills and the broader environment.

Portland cement, despite its widespread use in critical structures such as buildings and bridges due to its versatility, accessibility, and cost-effectiveness, is a significant contributor to global CO_2 emissions, accounting for approximately 9% of the total and consuming approximately 3% of global energy [57]. These figures underscore the urgent need for sustainable alternatives and improved waste management practices within the cement industry.

Despite these advancements, the management of CDW remains a critical issue. Strategies to address this include using CDW as fillers in cement, recycling it as aggregate, and employing it in combination with alkaline activators to enhance binding properties [58-64]. These approaches not only assist in reducing the environmental impact of concrete production but also contribute to the broader goals of sustainability in the construction sector. The research conducted by Rocha and Sousa-Coutinho [60] investigated the potential use of finely ground CDW as a partial replacement of Portland cement in concrete. In their study, they evaluated the effects of cement substitution at dosages ranging from 5% to 10% on durability and strength. Their findings indicated that CDW can slightly reduce strength but does not significantly affect durability, suggesting that a 5% substitution is suitable for general applications and up to 10% can be used in less demanding contexts.

Chen et al. [59] investigated a novel application of recycled red brick powder from CDW as a filler in waterborne coatings. Their findings demonstrated that such coatings exhibited significantly enhanced scrubbing resistance, up to nearly 5 times greater than the standards in China. The study detailed how the pigment volume concentration and the type of emulsion used influenced the coating's performance, with optimal results achieved using styrene-acrylic emulsion.

In their study, Cantero et al. [61] evaluated the impact of incorporating ceramic fractions of CDW as cement additions and recycled mixed aggregates in concrete. They analysed the properties of both the fresh and hardened concrete, including workability, density, air content, and strength. The study concluded that incorporating up to 50% recycled mixed aggregate and ceramic based CDW additions in cement did not significantly compromise concrete performance. This research serves to demonstrate the viability of integrating CDW into concrete, thereby contributing to the development of a circular economy and reduction the environmental effect of construction materials.

Rao et al. [62] investigated the potential of aggregates derived from CDW in concrete. Their research highlighted that CDW constitutes a significant proportion of global solid waste, with a substantial portion ending up in landfills. They proposed utilising this waste as aggregate in new concrete, particularly for non-structural applications. This study reviewed the international scenario concerning the generation of CDW, recycled aggregates produced from it, and their utilisation in concrete. It also identified obstacles, such as the lack of specifications for the use of recycled aggregates in new concrete, which impede the wider adoption of this approach.

In their discussion of the use of CDW as an aggregate in alkali-activated or geopolymer concrete, Sata and Chindaprasirt emphasise that CDW can effectively replace conventional aggregates and contribute to the eco-friendliness of construction practices by reducing landfill waste and preserving natural resources. Their study highlights the potential for CDW in making geopolymer concrete, which not only supports waste reduction but also enhances the durability and strength of the resulting concrete [64].

2.2.1. Use of CDW in Lightweight Foam Concrete

The incorporation of CDW into lightweight foam concrete represents a promising solution for the construction industry, offering both environmental benefits and economic viability. This material is distinguished by its low density, excellent thermal and acoustic insulation properties, and sufficient compressive strength, rendering it suitable for a multitude of construction applications, including non-load-bearing walls, insulation layers in flooring and roofing systems.

The incorporation of CDW into lightweight foam concrete not only facilitates the diversion of waste from landfills but also reduces the demand for virgin raw materials such as gravel and sand, which are typically employed in conventional concrete. This approach aligns with the principles of the circular economy, which emphasises the reduction, reuse, and recycling of materials to extend the lifecycle of resources and minimise waste.

Furthermore, the utilisation of CDW in lightweight foam concrete contributes to the sustainability of construction practices by reducing the carbon emissions associated with the production of cement. Cement production is one of the largest sources of CO_2 emissions globally, and by substituting a portion of the concrete matrix with processed CDW, the carbon footprint of concrete can be significantly reduced.

In the context of sustainable construction practices, CDW has been employed in various innovative ways to address environmental concerns associated with waste management and resource conservation. Primarily, CDW is utilized as a substitute for traditional aggregates in the production of foam concretes. This utilization helps to reduce the demand for natural aggregates, which in turn conserves natural resources and reduces the environmental footprint of construction activities [65].

Favaretto et al. [66] investigated the effect of different granulometries of CDW from the Passo Fundo region of Rio Grande do Sul, Brazil, which had not been previously characterised or reused for such purposes, on the properties of foamed concrete. Foamed concrete made with coarser CDW exhibited higher compressive strength than those with finer granulometry. The research highlighted the importance of the granulometry of the CDW in determining the final properties of the foamed concrete. Coarser granulometries generally provided better compressive strength, which is a critical consideration in selecting appropriate CDW properties for specific construction applications.

Sharipudin and Ridzuanise [67] investigated the use of waste paper sludge ash and FRCA as substitutes in foamed concrete and their effects on compressive strength. The maximum level of substitution is 20% for wastepaper sludge ash and 15% for FRCA. They concluded that the incorporation of wastepaper sludge ash and FRCA had a valuable effect on the mechanical properties of foamed concrete, with the best results being obtained at a ratio of 20% wastepaper sludge ash and 15% FRCA. In addition, the most important aspect of this study is that it highlights that up to 35% of conventional materials can be replaced with sustainable alternatives while maintaining or increasing the mechanical properties of foamed concrete.

Aliabdo et al. [68] investigate the use of crushed clay brick as an alternative aggregate in the production of cellular concrete, focusing on both autoclaved aerated concrete and foamed concrete. For foamed concrete, they determined replacement rates between 0-100% in the mixes they prepared, and the densities of the samples ranged between 1012 - 1137 kg/m³. The results indicated that an increase in the proportion of crushed clay bricks in foamed concrete led to a reduction in compressive strength, with a maximum decrease of 36%. This suggests that higher levels of replacement may compromise structural integrity. SEM microstructural analyses reveal that foamed concrete containing natural sand has a more uniform pore distribution compared to those containing higher proportions of crushed clay bricks, which show more connected and irregular pores. However, the use of higher percentages of crushed clay bricks in foamed concrete should be limited to avoid reducing the strength of the material.

Ibrahim et al. [69] conducted a study investigating the use of waste clay bricks as a substitute for natural aggregates in the production of lightweight foamed concrete. The study examined the effects of varying substitution percentages (25%, 50%, 75% and 100%) on the properties of the concrete. The findings indicate that as the percentage of waste clay bricks in the concrete increases, the density of the specimens also increases due to the higher water absorption properties of waste clay bricks compared to conventional aggregates. The density of the control specimen was 1631 kg/m^3, while that of the 100% substituted mix was 1734 kg/m^3. This increase in density may result in the concrete containing waste clay bricks being heavier than the control specimens without waste clay bricks. Nevertheless, the study notes a decline in compressive strength with increasing waste clay bricks content, with the highest strength observed at the 25% substitution level (the strength of the control specimen is 25.91 MPa, while that of the 100% substituted specimen is 6.25 MPa). This indicates that it is possible to replace natural aggregates with some waste clay bricks, but higher levels may compromise the structural integrity of the concrete. Moreover, water absorption tests have demonstrated that elevated proportions of waste clay bricks result in increased porosity within the concrete, which may have a detrimental impact on its durability and long-term performance.

Furthermore, CDW has been employed in geopolymer systems, where it serves as a binder. In these systems, the aluminosilicate content of CDW can be activated to form the geopolymer binder, effectively transforming waste materials into valuable construction products [64]. This not only contributes to the reduction of landfill waste but also diminishes the reliance on Portland cement, a significant contributor to CO_2 emissions in the construction sector.

Pasupathy et al. [70] conducted a study investigating the innovative use of ground brick waste in the production of geopolymer foam concrete. The study focused on improving the properties of foam concrete through alkali activation, particularly adjusting the alkali content to optimise the reaction kinetics and structural integrity of the material. The primary precursor for geopolymer synthesis was brick waste powder. The research methodology employed sophisticated analytical techniques, including FTIR and XRD, to monitor the chemical reactions and the evolution of the microstructure of the material. The results demonstrated that an increase in the alkali content significantly enhanced the mechanical properties of geopolymer foam concrete. For instance, an increase in the Na_2O concentration from 1:40 to 1:12 not only resulted in a 245% enhancement in compressive strength, but also a reduction in setting time from 315 minutes to 140 minutes. This indicates a direct correlation between alkali concentration and the capability of geopolymer foam. Moreover, the environmental analysis demonstrated that the utilisation of geopolymer foam concrete could result in a reduction of carbon emissions by up to 60% in comparison to OPC foam concrete. This highlights the potential of recycled brick waste as a viable alternative to traditional materials in the construction industry.

2.3 Energy Efficency

The characteristics of a building's envelope have a significant impact on its energy consumption. The thermal characteristics of exterior walls play a crucial role in boosting energy effectiveness within the construction sector and in lowering greenhouse gas emissions. One of the most effective methods for reducing energy use during both winter heating and summer cooling is the utilisation of appropriate thermal insulation [71]. Thermal insulation materials play a pivotal role in achieving energy efficiency. The correct selection, thickness, and positioning of insulation can significantly improve indoor thermal comfort and lead to substantial energy savings. The primary thermal properties of insulation materials, such as thermal conductivity, thermal resistance and specific heat capacity, directly influence the rate at which heat flows through the building envelope [72-74]. Aerogels are known for their ultra-low thermal conductivity and lightweight properties. However, they come at a higher cost and are used in high-performance applications. Additionally, insulations such as mineral wool, EPS, XPS, PUR, cellulose, and natural fibres offer a range of thermal properties. While thermal properties are of paramount importance in selecting insulation materials, other characteristics are also crucial. Sound insulation helps to minimise sound transmission, contributing to a quieter indoor environment. It is essential to consider fire resistance, with materials such as mineral wool being non-combustible, while organic materials may require flame retardants. The ability of a material to allow moisture vapour to escape, preventing mould growth and maintaining indoor air quality, is known as water vapour permeability. This characteristic should be considered alongside the environmental impact of the material, with cellulose, natural fibres and mineral wool generally being eco-friendly. Potential health impacts, such as formaldehyde in some foam insulations, should also be assessed.

Previous studies have indicated that variations in heat flux are contingent upon the thermal capacity of wall construction materials [75]. In order to assess the thermal behaviour of building materials within the building, the primary parameters which are determined by the temperature differences between inner and outer surfaces. The optimal thermal comfort is achieved with building materials that exhibit a good primary parameter. These dynamic thermal characteristics have been extensively studied in the context of lightweight concrete, with a particular focus on the role of voids within the concrete matrix in resisting the transfer of heat from the outdoor to the indoor environment [76]. In the case of lightweight concrete, these voids represent a significant feature that helps to resist heat transfer. By carefully designing the composition and structure of lightweight concrete, by enhancing the time lag and minimizing the decrement factor, it is feasible to bolster the overall thermal performance of the building envelope. These characteristics ensure that heat from the external environment is absorbed and released at a slower rate, creating a more stable indoor temperature and reducing the necessity for active heating and cooling systems [77-79].

The literature contains analyses of the optimal thicknesses and costs of insulation materials. Yu et al. [80] investigate the use of thermal insulation to increase energy savings in buildings in four cities in the high temperature summer and winter regions of China. A total of five insulation materials (expanded polystyrene, extruded polystyrene, foamed polyurethane, perlite and foamed polyvinyl chloride) were analysed in order to determine their optimum thicknesses. This was achieved through the use of solar-air cooling and heating degree-day analysis. The optimum insulation thicknesses were found to range from 0.053 to 0.236 m, with payback periods of 1.9 to 4.7 years over a 20-year lifetime. The highest life cycle savings were observed in Shanghai, at 54.4 \$/m², followed by Changsha (54.8 \$/m²), Shaoguan (41.5 \$/m²) and Chengdu (39.0 \$/m²).

In their study, Ustaoglu et al. [81] evaluate the energy performance of lightweight concrete containing different proportions of vermiculite by combining analytical simulations of energy consumption with experimental tests of thermal properties in climatic regions of Turkey. The expanded vermiculite improves lightweight concrete consequence of its low density and superior thermal and acoustic properties. The energy saving effect increases from climate zone 1 (eastern Turkey) to climate zone 4 (Mediterranean coastal region), with the best performance being obtained from CON1 concrete (thermal conductivity of 0.269 W/mK). In zone 4, the greatest reduction in total heat demand is 5.6 kWh/m²-yr for a 0.2 m thickness of CON1, while the most significant percentage reduction (approximately 6%) occurs in zone 1. LPG resulted in the highest energy cost, followed by electricity, fuel oil, coal and natural gas. The use of LPG in zone 4 resulted in savings of up to \$0.61 per square metre per year, while coal was found to be almost twice as cost-effective as natural gas across all zones. Payback periods ranged from 1.29 years for LPG to 8.34 years for natural gas. The study concluded that vermiculite-reinforced lightweight concrete can significantly improve building energy performance and offer promising developments for green buildings.

The Ucar ve Balo study [82] calculates the optimal insulation thickness for external walls in 4 cities across 4 climate zones in Turkey. The study examines the potential for energy savings over a 10-year period and the associated payback periods for 5 different types of energy and 4 insulation materials (extruded polystyrene, expanded polystyrene, nil siding, and rock wool). The method was employed to ascertain net energy cost savings, which exhibited a range of values between \$4.20 and \$9.50 per square metre, contingent on the city and insulation material. The findings indicate that energy cost savings are directly proportional to fuel costs, insulation material, and climatic conditions. The highest energy cost savings were observed when using LPG, while natural gas provided the lowest savings. The longest payback period (2.25 years) was observed in Mersin, where natural gas was used for heating, while the shortest payback period was achieved with LPG in

Bitlis. Overall, the study concludes that optimal insulation thickness can significantly reduce energy costs, with the optimal thickness varying based on the energy source, insulation material, and climate.

The selection of insulation materials must take into account the crucial issue of sustainability. The most sustainable insulation materials have a minimal environmental impact throughout their life cycle, from production to disposal. The use of recycled materials is an important factor in this regard, as insulation made from recycled materials reduces the demand for virgin resources. Additionally, the energy required to produce and transport insulation materials, known as embodied energy, affects their overall environmental impact. The reduction of CO_2 emissions is of critical importance in the fight against climate change. Proper insulation can significantly reduce a building's carbon footprint by reducing energy consumption for heating and cooling. In conclusion, the optimal choice of insulation materials and lightweight concrete can result in significant energy savings. However, the optimal choice of materials and techniques depends on the energy source, insulation material, and climate. Proper insulation selection and design can contribute significantly to reducing energy consumption, promoting sustainability, and achieving global climate goals.

3.MATERIALS AND METHODOLOGY

3.1. Materials

3.1.1 Eco-Hybrid Cement

In this study, a novel cement variant known as "Eco-hybrid cement" was utilized as the primary binder. This innovative blend comprised 63% by weight of CEM I 42.5R OPC, 5% by weight of CSA cement, and 32% by weight of CDW. This composition was meticulously crafted to harness the combined advantages of enhanced environmental sustainability, efficient waste management and recycling, superior early-stage strength, and reduced setting time.

Eco-hybrid cement, a proprietary formulation developed as part of circular economy initiatives targeting construction and demolition waste, was procured from ÇİMSA, a cement company in Turkey. The CDW used in producing Eco-hybrid cement comprised a blend of 20% HB, 20% RCB, 20% RT, and 40% CW by weight. These CDW-derived materials were sourced from urban renewal sites and underwent a crushing and grinding process to achieve a particle size distribution comparable to that of OPC particles. CDW based materials is showed that in Figure 3.1.

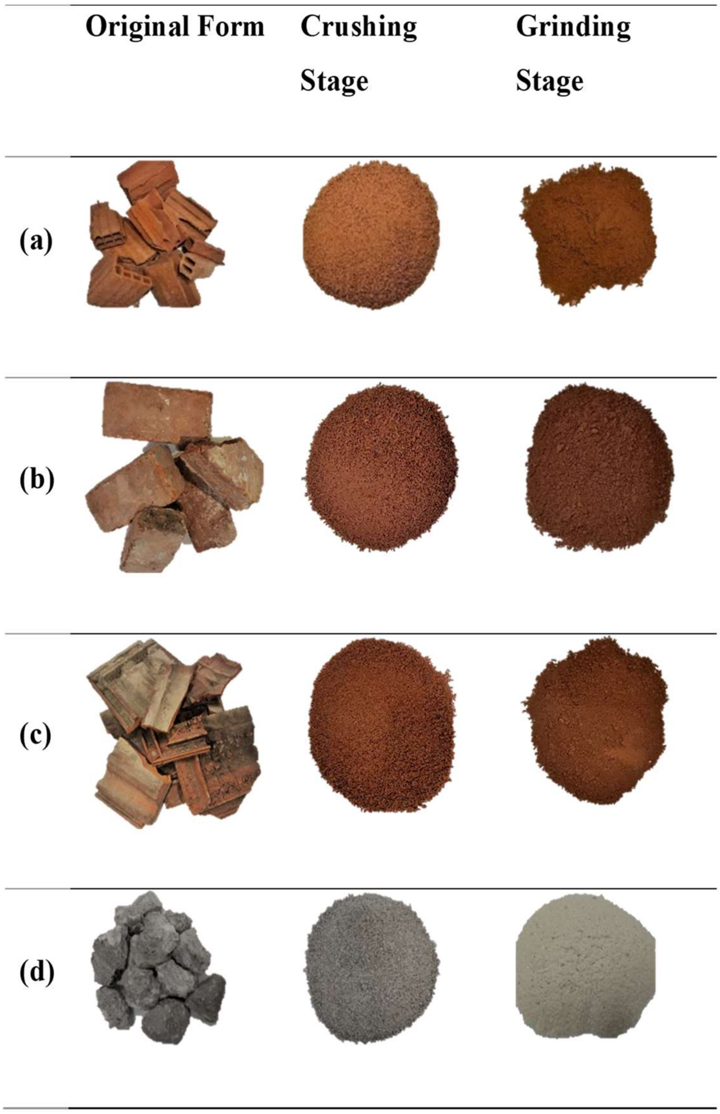

Figure 3.1. Photographs of CDW-based materials: (a) Hollow Brick, (b)Red Clay Brick (c) Roof Tile (d) Concrete Waste

The chemical compositions of the constituent elements of Eco-hybrid cement were meticulously analysed through X-ray fluorescence (XRF) analysis, as outlined in Table 3.1. Additionally, the mechanical properties of Eco-hybrid cement were rigorously evaluated in accordance with EN 196 standards, with the results presented in Table 3.12. This comprehensive approach underscores the multifaceted advantages and robust performance of Eco-hybrid cement in sustainable construction practices.

Table 3. 1. Chemical compositions of components of Eco-hybrid cement

Materials	**Chemical composition (%)**								
	SiO_2	**Al_2O_3**	**Fe_2O_3**	**CaO**	**MgO**	**SO_3**	**Na_2O**	**K_2O**	**LoI***
OPC 42.5 R	19.4	5.12	2.79	63.5	2.58	3.05	0.28	0.87	2.65
CSA	7.77	35.7	2.69	42.5	1.18	7.85	0.07	0.23	0.33
HB	39.7	13.8	11.8	11.6	6.45	3.40	1.45	1.55	7.80
RCB	41.7	17.3	11.3	7.69	6.49	1.41	1.15	2.66	7.96
RT	42.6	15.0	11.6	10.7	6.26	0.71	1.60	1.60	7.49
CW	31.6	4.76	3.50	31.3	5.12	0.92	0.45	0.71	20.9

*: Loss on ignition

Table 3. 2. Properties of different type of cements

Property	**OPC CEM I 42.5R**	**CSA cement**	**Eco-hybrid cement**
Initial setting time (min.)	175	275	115
Final setting time (min.)	220	330	200
Water amount for setting (%)	29.4	28.0	33.4
Flow (cm)	15.0	20.0	12.0
Soundness (expansion, mm)	1.00	0.10	10.0
7-day mortar compressive strength (MPa)	41.7	86.2	27.5
28-day mortar compressive strength (MPa)	51.2	90.5	33.3

3.1.1. Fine Recycled Concrete Aggregate (FRCA)

FRCAs were produced by crushing concrete rubbles in a laboratory-scale jaw crusher. Prior to commencing the crushing process, the concrete waste was first broken into pieces that were small enough to fit into the crusher. The crushed material was then passed through a series of sieves to obtain RCAs within the desired size range. In this study, RCAs passing through a 1 mm sieve were used. Figure 3.2. illustrates the pieces derived from concrete waste and introduced into the jaw crusher, while Figure 3.3. depicts the sieves employed. Figure 3.4. presents a photographic representation of the FRCAs obtained.

Figure 3. 2. Concrete rubble for the purpose of crushing

Figure 3. 3. Sieves used for aggregate gradation

Figure 3. 4. Photograph of FRCA

3.1.2.1. Density of aggregates

The densities of the aggregates were determined in accordance with the procedures set out in TS EN 1097. Initially, the samples were submerged in water at 20°C for 24 hours to ensure saturation, allowing all pores within the aggregates to be filled with water. A 500-gram sample was utilised. Subsequently, the weight of the coarse aggregates submerged (M2) and the weight of the empty basket housing the aggregates (M3) were measured. The values of M2 and M3 were determined using a pycnometer for fine aggregates. The aggregates were then brought to a surface saturated dry (SSD) condition and weighed (M1). Subsequently, the aggregates were dried in an oven set to 115°C until they reached a constant mass, and their weights were recorded (M4). All measurements were recorded in grams. The densities of the aggregates (ρa, ρrd, and ρSSD) were calculated utilising the following formulas:

$$\rho_a = \rho_w \frac{M4}{M4-(M2-M3)} \quad (1)$$

$$\rho_{rd} = \rho_w \frac{M4}{M1-(M2-M3)} \quad (2)$$

$$\rho_{SSD} = \rho_w \frac{M1}{M1-(M2-M3)} \quad (3)$$

where,

ρ_a: Apparent density, g/cm^3

ρ_{rd}: Oven Dry density, g/cm^3

ρ_{SSD}: SSD density, g/cm^3

ρ_W: Density of water, g/cm^3

The scale used to measure the density of FRCAs and fine normal aggregates (FNA) are illustrated in Figure 3.5, while the density results obtained are presented in Table 3.3.

Figure 3. 5. Scale used in the experiment

Table 3. 3. Densities of FRCA and FNA

Property	**FRCA**	**FNA**
Dry specific gravity (g/cm^3)	1.86	2.64
Saturated surface dry specific gravity (g/cm^3)	2.11	2.67
Apparent specific gravity (g/cm^3)	2.51	2.72
Loose unit weight (g/cm^3)	1.44	1.67
Dense unit weight (g/cm3)	1.58	1.80

3.1.1.1. Water absorption

The water absorption values provided in Table X indicate that FRCA exhibited 13.8% water absorption. The consistency between water absorption and density results can be attributed to the presence of adhered mortar on the aggregate surface. Adherent mortar, being inherently porous, absorbs significant amounts of water. Consequently, higher amounts of adhered mortar lead to decreased aggregate density and increased water absorption rates. Furthermore, variations in water absorption capacity reported in the literature stem from differences in cement paste content within the aggregates, as well as the presence of other components. Water absorption results are presented in Table 3.6.

Table 3. 4. Water absorption of FRCA and FNA

Property	**FRCA**	**FNA**
Water absorption (%)	13.8	1.24

3.1.2. Sieve analysis

The particle size distributions of the CDW-based materials (HB, RCB, RT, and CW), CEM I 42.5R, and the CDW-based FRCA are illustrated in Figure 3.6. It was observed that the CDW-based materials demonstrated comparable particle size distributions, whereas CEM I 42.5R exhibited a slightly coarser particle size distribution compared to the CDW-based materials. Figure 3.6 presents particle size distributions.

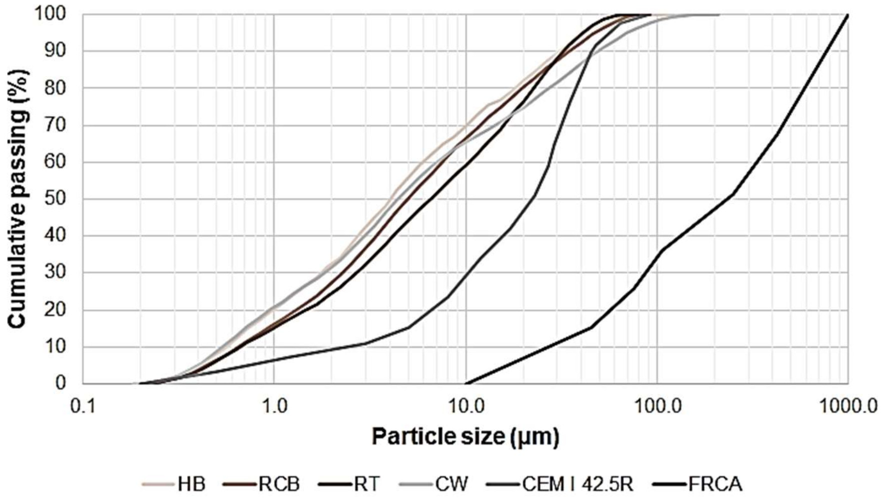

Figure 3. 6. Particle size distributions of the materials

3.1.3. Foaming Agent

The mixtures utilised MasterRoc® SLF 30 type foaming agent, which was in liquid form. This foaming agent had a density ranging from 1035 to 1045 kg/m³ and a pH value between 6.5 and 7.5.

3.1.4. Silica-aerogel

Silica-aerogel, obtained from KEEY Aerogel company in France, was employed in the study. This circular silica-aerogel had previously been investigated in another study to explore its impact on plasterboard recycling [83]. It was produced from CDW-based glass and siliceous concrete wastes using hydrothermal synthesis. The physical properties of SA are detailed in Table 3.7. Additionally, particle size distribution along with its visual representations and SEM micrographs of silica-aerogel, were depicted in Figures 3.7 and 3.8, respectively. The SEM micrograph demonstrated that the nanoparticles were interconnected in a three-dimensional structure, forming a skeletal network.

Table 3. 5. Properties of silica-aerogel

Property	**Result**
Bulk density (g/cm^3)	0.08-0.10
BET surface area (m^2/g)	949
Average pore size (nm)	5.1

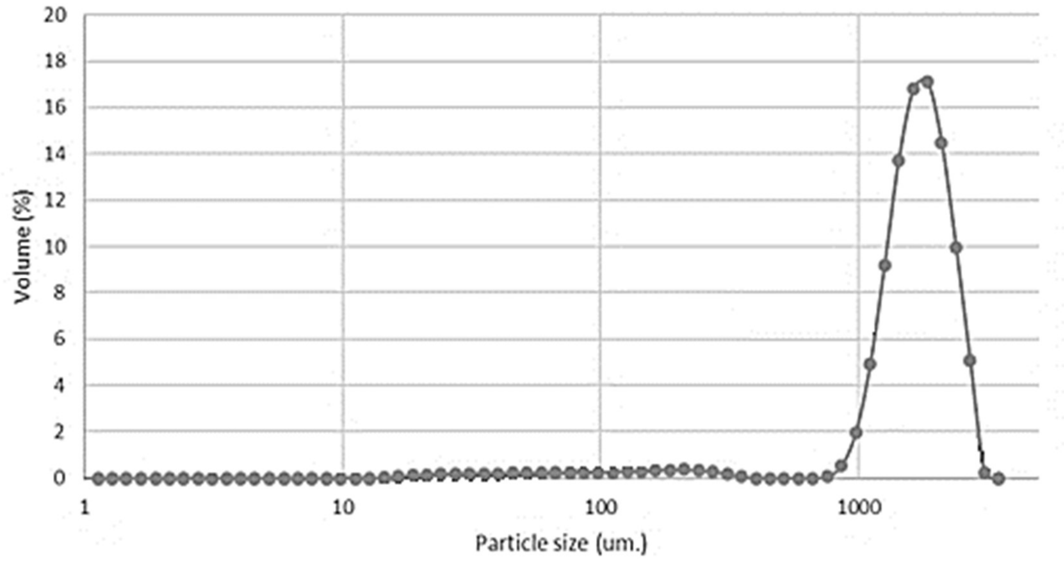

Figure 3. 7. Particle size distributions of silica-aerogel

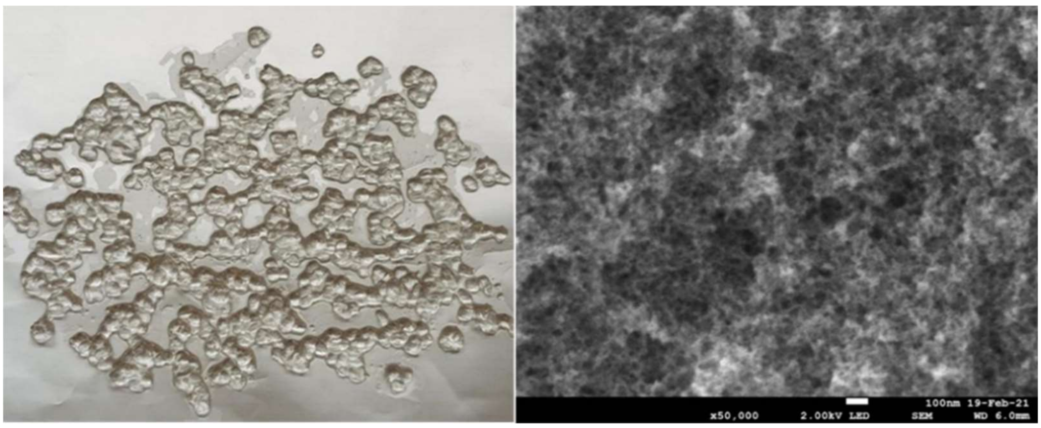

Figure 3. 8. Visual and SEM micrographs of silica-aerogel

3.2.Methodology

This chapter presents a comprehensive overview of the design of mixtures, mixing, casting and placement of fresh mortar into moulds, as well as the various conditions of the samples, including compressive strength, flexural strength, fresh and dry density, stability, flowability and thermal insulation. The entire process is described in detail.

3.2.1. Preparation of mixtures

The mixtures were prepared according to varying ratios of Eco-Hybrid, water/binder ratio, FRCA content and silica-aerogel content relative to the total mortar volume. The foaming agent content was calculated based on the volume of water used in the foam mixture, and the mixtures were prepared accordingly. The mixture design process followed several steps:

1. Determining the volume of the foam mixture.
2. Calculating the volume of the mortar mixture by subtracting the foam mixture volume from the targeted total volume (1 m3).
3. Calculating the required amount of the planned varying parameter in the mixtures based on the volume of the mortar mixture.

As a consequence of the extensive testing conducted, the final and detailed mixture designs are presented in the result and discussion section. The materials utilised in the mixtures were weighed to 0.01 g on a precision scale and subsequently mix in the mixer.

3.2.2. Mixing, casting and curing

Firstly, foam was generated by mixing the foaming agent and water for four minutes at 100 rpm. Secondly, the dry mixture of Eco-hybrid cement and FRCA was homogeneously blended for one minute, followed by the addition of water to produce the mortar mixture. Finally, the prepared mortar and foam were mixed for two minutes at 100 rpm, followed by an additional two minutes at 200 rpm. In the SA-coded mixtures, silica-aerogel was introduced to the mixture and mixed for an additional two minutes at 200 rpm. Figure 3.9 provides a summary representation of all materials utilised in the production of lightweight foam concrete fresh mixture.

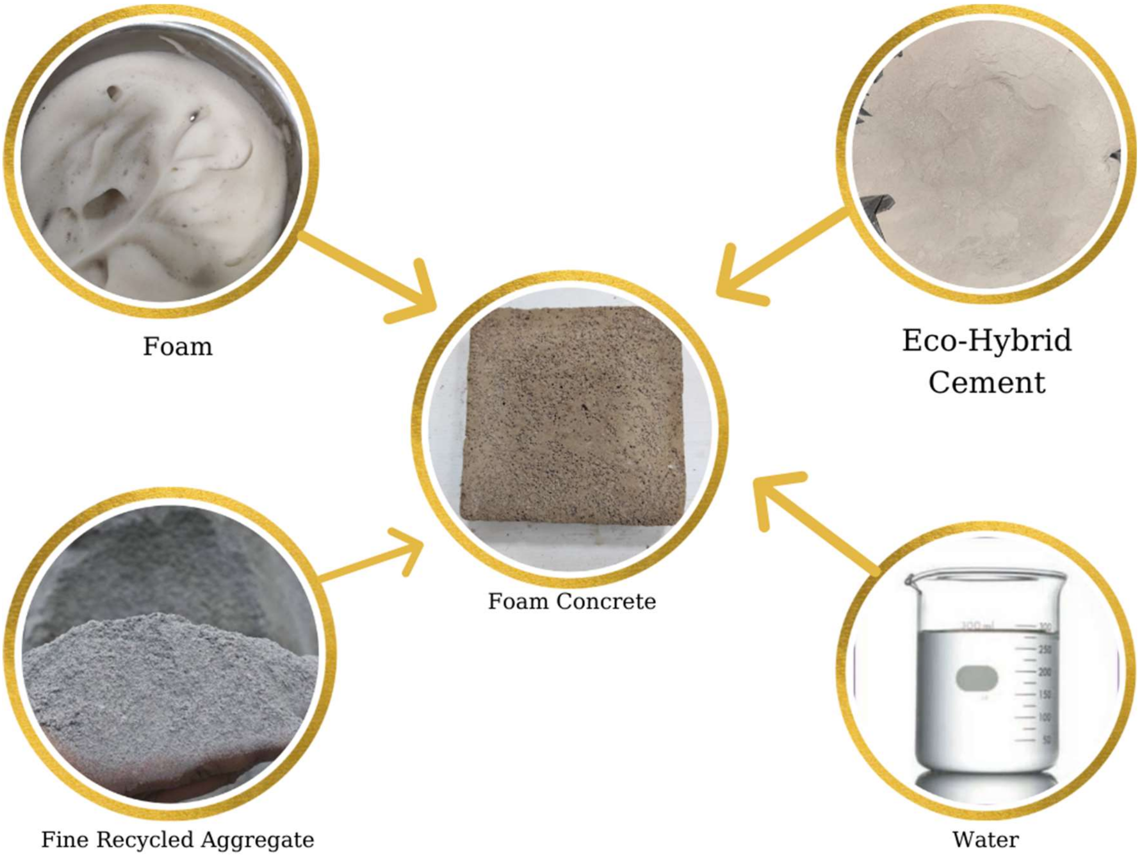

Figure 3.9. Summary representation of all materials utilised in the production of lightweight foam concrete and fresh mixture.

The mixtures were poured into three cubic molds measuring 50×50×50 mm, as well as three coupon molds with dimensions of 15×80×240 mm. Additionally, for thermal conductivity analysis, the SA-coded mixtures were cast into panel molds measuring 36×300×300 mm. During the casting process, it was ensured that no excessive vibration was applied, as this could lead to segregation in ultra-lightweight concrete, as previously observed in a study [84]. The samples were carefully and homogeneously cast without the use of vibration. Subsequently, the samples were left in the molds for a period of four days, with their surfaces covered, under controlled conditions of 23±2 °C temperature and 50±5% relative humidity. Subsequently, the samples were extracted from the molds and subjected to curing under dry ambient conditions until they reached the designated testing age. Figure 3.10 illustrates the moulds prepared for the tests and the dimensions of the specimens in greater detail.

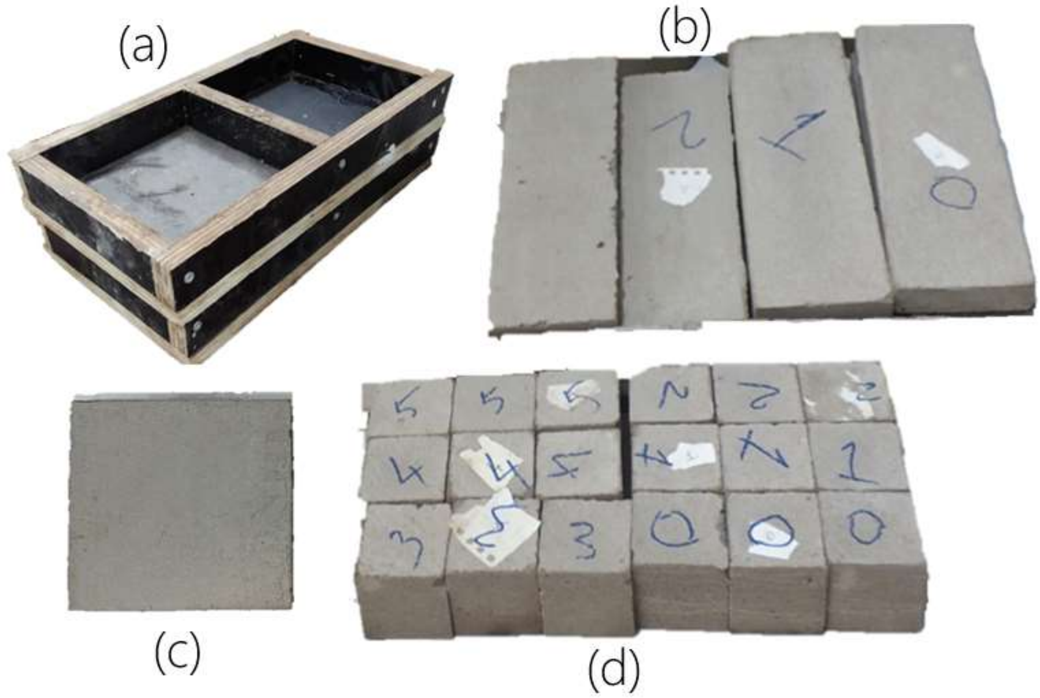

Figure 3. 10. (a) 36×300×300 mm panel moulds, (b) 36×300×300 mm panel specimen, (c) 15×80×240 mm panel specimens, (d) 50×50×50 mm cube specimens

3.2.3 Testing

In the initial state, measurements of the fresh weight and density were conducted. Additionally, the flowability of the material was assessed using a flow table to determine the extent to which it could be spread in perpendicular directions. The stability of the mixtures was determined by comparing the fresh and dry densities, with deviations indicating potential issues with stability. Compressive strength tests were conducted on cubic specimens according to ASTM C39 standards, utilizing a loading device with a 5-ton capacity at a loading rate of 0.3 kN/s. Figure 3.11 illustrates the compressive strength test of a 50×50×50 mm cube specimen.

Figure 3. 11. Compressive strength test

Flexural strength measurements were conducted on coupon specimens with a span length of 70 mm according to ASTM D6272 standards, using a deformation-controlled electro-mechanical test device with a 1-ton capacity at a loading rate of 0.005 mm/s. Figure 3.12 illustrates the flexural strength test of a 15×80×240 mm panel specimen.

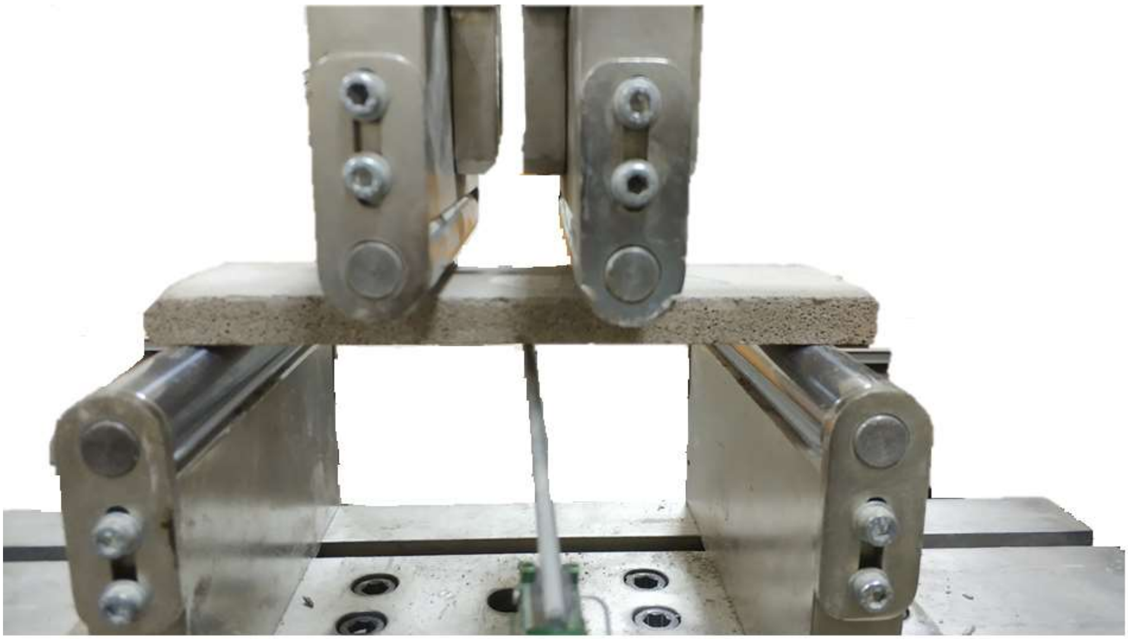

Figure 3. 12. Flexural strength test

A thermal conductivity analysis was conducted on panel specimens using a TA Instruments FOX 314 Thermal Conductivity Analyzer. This analysis was specifically focused on the SA-coded mixtures in order to determine the influence of SA on thermal properties.

A series of SEM/EDX analyses were conducted using a Tescan GAIA3+Oxford XMax 150 EDS device with the objective of examining the matrix characteristics and atomic distributions in depth. Additionally, micro-CT analyses were performed using a Bruker Skyscan 1272 device with the aim of observing the pore size distribution and pore interconnections in the selected mixtures.

4. RESULTS AND DISCUSSION

This section presents a detailed analysis of the results and findings obtained from studies utilising Eco-Hybrid cement as a binder and FRCA as an aggregate. The mixtures were prepared according to varying ratios of Eco-Hybrid, water/binder ratio, FRCA content and silica-aerogel content relative to the total mortar volume. The mixture calculation method described in Section 3.2.1. "Preparation of Mixtures," will be employed in this section to provide the formulas for the final mixtures. In order to elucidate the rationale behind the calculation of the mixtures in the mixture coded FRCA1, it was first necessary to quantify the FRCA content. This amount was found to be 5 per cent of the volume of the mortar mix. Subsequently, with a fixed water/binder ratio of 0.33 (for all mixes except for the mixes coded WB), the amount of water in the mortar mix was calculated by volume. Finally, the quantity of FRCA required to fill the remaining volume of the mortar mix was determined. It was observed that there were minor discrepancies between the intended and actual volumes. This can be attributed to the interaction between aggregate and foam during the mixing process. This issue of inconsistency in volume was addressed in a previous study [85], which emphasised the difficulty of precise control of volumes in these mixes compared to conventional concrete mixes. The formulated mixtures were then subjected to ambient curing, after which the optimal ratios were evaluated. Once the optimal ratios had been established, the thermal insulation of the 14 and 28-day samples was evaluated. This was achieved through the use of SEM and energy-dispersive X-ray spectroscopy (EDX) experiments. The samples taken from the 28-day samples were analysed using micro-computed tomography to examine the effect of silica-aerogel content on thermal insulation. This involved examining the open, closed and total porosity properties of the samples. The results of these analyses have enabled the identification of the optimum compressive strength, flexural strength, spreading diameter and, most importantly, the final products that provide thermal insulation.

4.1 Optimizing Eco-Hybrid cement content

The C-coded series comprised five distinct mixture designs characterized by incremental variations in Eco-hybrid cement content, ranging from 30% to 50% relative to the total mortar volume. For the C-coded series, the constituents and their respective proportions within the mixtures are delineated in Table 4.1, and photographs of the samples are shown in Figure 4.1.

Figure 4. 1. Samples of C-coded series

Table 4. 1. C-coded mixtures

Variance*	Mixture ID.	Mixture proportions (kg/m^3)						Volume (m^3)	
		Mortar mixture				Foam mixture			
		Eco-hybrid cement	Water	FRCA	SA	Foaming agent	Water**	Target	Actual
30%	C1	250.8	82.8	334.2	-	1.5	100	1.0	0.91
35%	C2	292.6	96.5	260.9	-	1.5	100	1.0	1.01
40%	C3	334.3	110.3	187.6	-	1.5	100	1.0	0.99
45%	C4	376.1	124.1	114.2	-	1.5	100	1.0	0.99
50%	C5	417.9	137.9	40.92	-	1.5	100	1.0	1.03

* Calculated by mortar volume except F-coded series. In F-coded series, foaming agent content was calculated by water volume in foam mixture.

** Water used in the production of foam mixture, excluding the water in the mortar mixture

4.1.1. Effect of Eco-hybrid cement content on the physical properties

This segment of the study examines the consequences of augmenting the proportion of eco-hybrid cement in ultra-lightweight concrete from 30% to 50% at 5% intervals on both its fresh and hardened properties. The data presented in Table 4.2 demonstrates a consistent increase in the mean flow diameter across all compositions as the eco-hybrid cement ratio rises. Specifically, this increase from 30% to 50% results in an elevation in the mean flow diameter from 212 mm to 263 mm, reflecting an approximate 24% surge. This surge can be attributed to the intensified presence of cement, which engenders a denser paste that envelops the aggregate surface, thereby mitigating inter-aggregate friction and enhancing the material's workability and fluidity [86]. Furthermore, the uniform water-to-binder ratio employed in these mixtures contributes to a gradual increase in the total water content as the cement proportion is elevated. This phenomenon may be exacerbated by the varying content of FRCA, which is known for its substantial water absorption capacity. Consequently, as the cement proportion increases, the FRCA content decreases in order to maintain a uniform mortar volume. This results in a progressive decline in the total mortar mass and density from C1 to C5. Furthermore, Figure 4 elucidates the trend of declining fresh and dry densities as the cement content increases. For example, the fresh density values for mixtures designated as C1, C2, C3, C4, and C5 were 0.843, 0.744, 0.741, 0.722, and 0. The corresponding dry density values were 0.666, 0.602, 0.593, 0.587, and 0.538 g/cm^3, respectively (Figure 4.2). This reduction in density, approximately 19.22% as the cement content rises from 30% to 50%, contrasts with the anticipated pattern of increasing density with higher cement content. The uniform water-to-binder ratio contributes to the heightened water content as cement content increases, necessitating a decrease in FRCA content to uphold a consistent mortar volume, thereby resulting in a gradual decline in total mortar mass and density. Furthermore, the rigidity of the mixtures influences the observed density values. Mixtures exhibiting lower fluidity (e.g., C1) display higher density compared to those with higher fluidity (e.g., C5). This can be attributed to the tendency of air bubbles to rupture with increased rigidity, leading to a decrease in overall volume and consequently, an increase in density. Moreover, stability values ranging from C1 to C5 were determined as 1.266, 1.236, 1.250, 1.230, and 1.266, respectively (Table 4.2). However, no linear correlation was observed between cement content and stability values. The highest stability values recorded in the series were for the C1 and C5 mixtures. This can be attributed to two factors. Firstly, the high-water absorption rate of FRCA in the C1 mixture results in decreased mixing water, leading to increased stiffness and reduced foam volume. Secondly, the C5 mixture, characterised by higher fluidity, results in a slurry too thin to maintain air bubble cohesion, leading to foam segregation. These findings align with previous research results [8, 87].

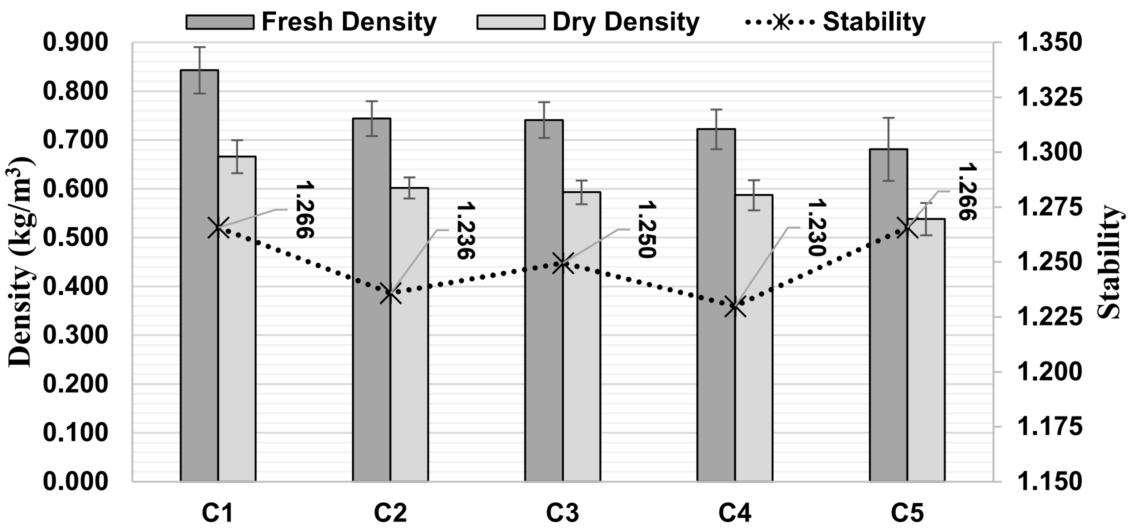

Figure 4. 2. Densities and stabilities of C-coded series

Table 4. 2. Flow diameter of C-coded series

Mixture ID.	Flow diameter (mm)
C1	212.0
C2	223.5
C3	234.0
C4	248.5
C5	263.0

4.1.2. Effect of Eco-hybrid cement content on the mechanical properties

Figure 4.3 depicts the compressive and flexural strength outcomes of the C-coded mixtures following 28 days of curing. The C1-coded mixture exhibited the lowest compressive and flexural strength values of 0.35 and 0.18 MPa, respectively, while the C5-coded mixture demonstrated the highest compressive and flexural strengths of 1.37 and 0.42 MPa, respectively. The findings indicate that higher proportions of eco-hybrid cement in the mixtures corresponded to improved compressive and flexural strengths. Specifically, a 5% increase in eco-hybrid cement content from 30% to 50% resulted in a 37.94%, 67.82%, 181.84%, and 296% increase in compressive strength, respectively. Conversely, flexural strengths increased by 30.42%, 32.57%, 120.57%, and 132.25%, respectively. Although a linear correlation between the rate of strength increase and eco-hybrid cement dosage was not established, a consistent enhancement in compressive and flexural strengths was observed with higher cement concentrations. This enhancement can be attributed to reduced porosity as cement concentration rises, resulting in a denser and stronger matrix [88].

It is noteworthy that the flexural-to-compressive strength ratios for the C-coded mixtures were 0.52, 0.49, 0.41, 0.41, and 0.30 for C1, C2, C3, C4, and C5, respectively. In contrast to typical flexural-to-compressive strength ratios of normal weight concretes falling within the range of 0.08 to 0.11, foam concretes typically exhibit higher ratios ranging from 0.2 to 0.4 [7]. This behavior is attributed to the unique response of lightweight foam concrete to flexural loads. Prior research has shown that foam concrete with a density of 400 kg/m^3 has poor flexural strength despite non-negligible compressive strength due to significant porosity and air bubble coatings on hydration products. However, in foam concretes with densities of 600-800 kg/m^3, reduced porosity leads to a larger volume of solid structure and the development of flexural strength, resulting in higher flexural-to-compressive strength ratios [89]. These findings align with the outcomes of this study. Additionally, prior studies have suggested that incorporating fibers, rather than increasing cement dosage, has a notable positive effect on foam concrete's flexural strength [90, 91].

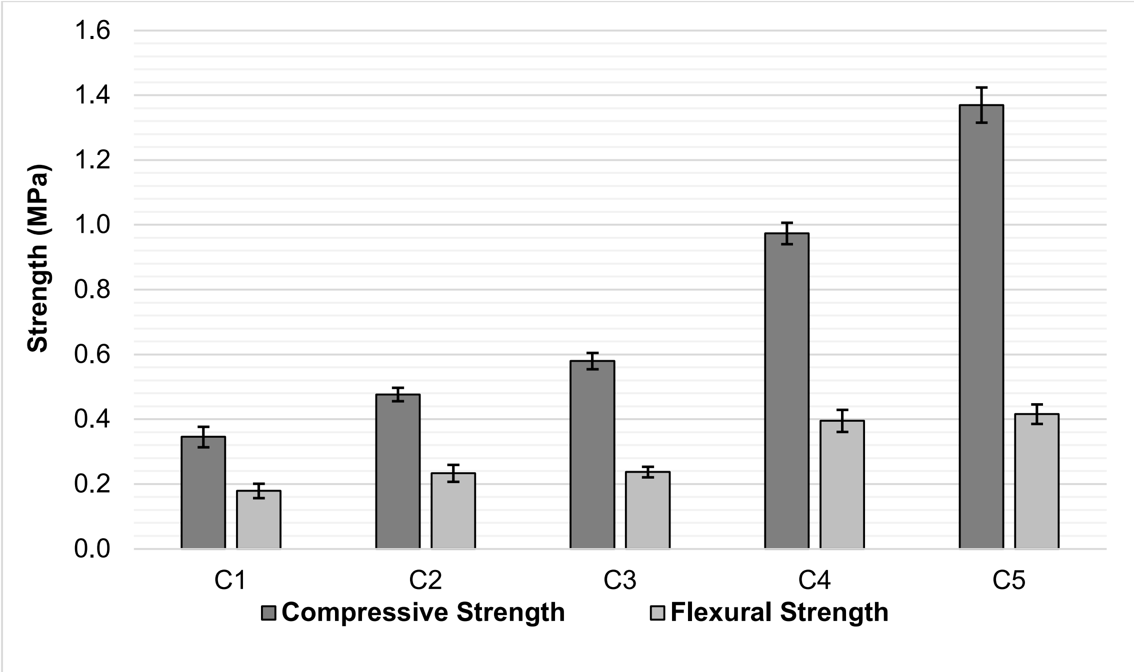

Figure 4. 3. Compressive and flexural strength results of C-coded series

4.2. Optimizing water/binder ratio

The mixtures within the WB-coded series, identified as such, consisted of five different designs with water/binder ratios ranging from 0.27 to 0.39 at intervals of 0.03. These mixtures are detailed in Table 4.3, and photographs of the samples are shown in Figure 4.4.

Table 4. 3. WB-coded mixtures

Variance*	Mixture ID.	Mixture proportions (kg/m^3) Mortar mixture: Eco-hybrid cement	Water	FRCA	SA	Foam mixture: Foaming agent	Water**	Volume (m^3): Target	Actual
0.27	WB1	406.2	109.7	122.9	-	1.5	100	1.0	0.95
0.30	WB2	390.8	117.2	118.2	-	1.5	100	1.0	0.94
0.33	WB3	376.5	124.2	113.9	-	1.5	100	1.0	0.94
0.36	WB4	363.2	130.7	109.9	-	1.5	100	1.0	0.97
0.39	WB5	350.8	136.8	106.1	-	1.5	100	1.0	0.99

* Calculated by mortar volume except F-coded series. In F-coded series, foaming agent content was calculated by water volume in foam mixture.

** Water used in the production of foam mixture, excluding the water in the mortar mixture.

Figure 4. 4. Samples of WB-coded series

4.2.1. Effect of w/b ratio on the physical properties

The focus of this section was to examine the influence of different water-to-binder ratios (0.27, 0.30, 0.33, 0.36, and 0.39) on the fresh properties of the mixtures. The findings presented in Table 4.4 showed that the flow diameters of the mixtures varied from 239.0 to 253.5 mm, with a gradual rise observed in the flow diameters as the water-to-binder ratio increased. This trend is consistent with the expected effect of increased water content on mixture fluidity. However, the degree of increase in fluidity was not as pronounced as that observed in the C-coded mixtures. This could be attributed to the lower variability in the quantities of other mixture components, such as eco-hybrid cement and FRCA.

Figure 4.5 illustrates the fresh and dry densities, along with stability values, of the WB-coded mixtures. The results indicated a decline in both fresh and dry densities as the water-to-binder ratio increased. Specifically, the fresh density decreased by 10.25%, while the dry density decreased by 19.17% when the water-to-binder ratio rose from 0.27 to 0.39. Although the effect of mixing water was similar to that observed in the C-coded series, the changes in density values were comparatively minor. Furthermore, the stability values of the mixtures exhibited an increase from 1.187 to 1.318 as the water-to-binder ratio increased from 0.27 to 0.39. This trend was hypothesized to stem from a reduction in particle concentration in the slurry, as indicated by prior research [92], potentially leading to increased difficulty in the overlapping of hydration products.

Table 4. 4. Flow diameter of WB-coded series

Mixture ID.	**Flow diameter (mm)**
WB1	239.0
WB2	243.5
WB3	248.0
WB4	250.5
WB5	253.5

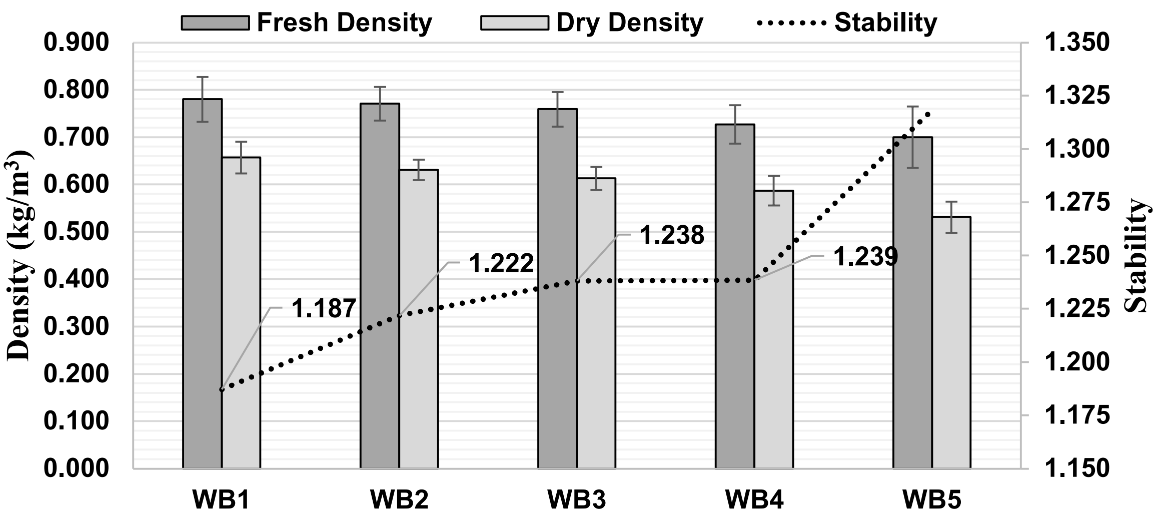

Figure 4. 5. Densities and stabilities of WB-coded series

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4.2.2. Effect of w/b ratio on the mechanical properties

Figure 4.6 depicts the compressive and flexural strength outcomes of the WB1, WB2, WB3, WB4, and WB5 coded mixtures. The compressive strength values were recorded as 1.24, 1.05, 0.98, 0.98, and 0.75 MPa, respectively. Similarly, the flexural strength values were observed as 0.45, 0.39, 0.32, 0.30, and 0.29 MPa, respectively. The findings revealed a consistent decline in both compressive and flexural strengths as the water-to-binder (w/b) ratio increased. Specifically, there was a reduction of 39.5% in compressive strength and 34.7% in flexural strength as the water-to-binder ratio rose from 0.27 to 0.39. The conventional water-to-binder ratio for achieving complete hydration of cement paste without capillary porosity is typically reported to be around 0.32. However, the presence of other constituents, such as FRCA, water for foam mixture, and foaming agent, in the mixtures might have contributed to this observed trend. Additionally, a prior study noted that the viscosity and yield stress of cement paste diminish with increasing water-to-binder ratio, leading to heightened porosity and reduced strength of the mixture [88].

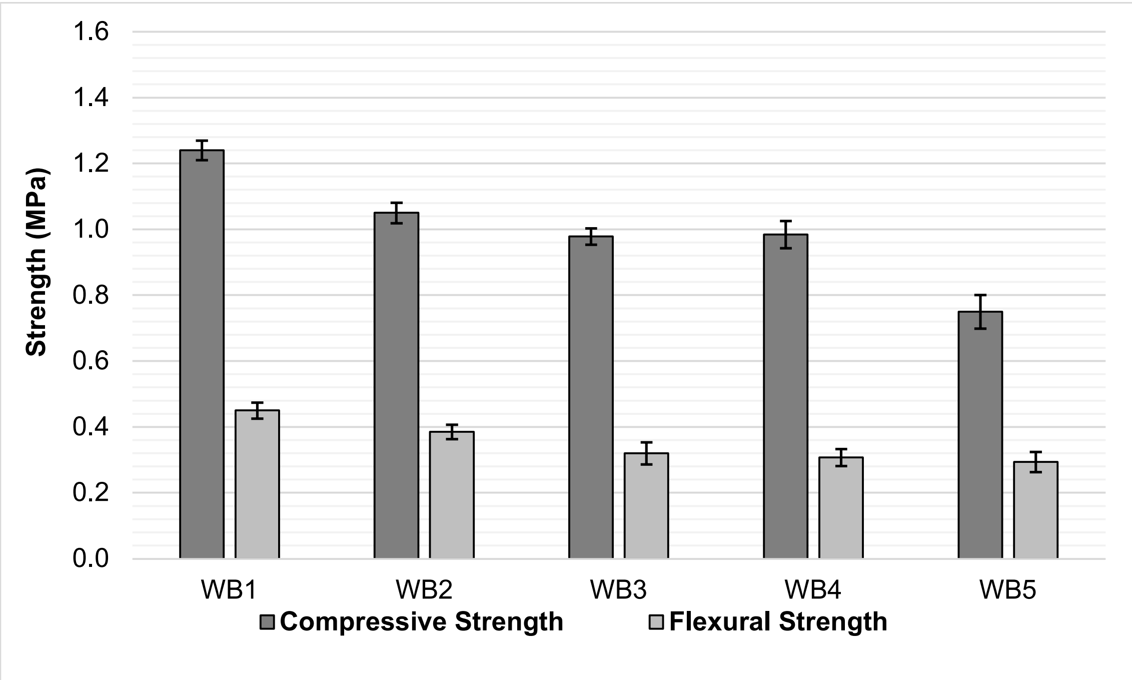

Figure 4. 6. Compressive and flexural strength results of WB-coded series

4.3. Optimizing FRCA Content

The series referred to as FRCA-coded comprised five distinct mixture designs utilizing FRCA at rates of 5%, 10%, 15%, 20%, and 25% relative to the total mortar volume. These designs are outlined in Table 4.5.

Table 4. 5. FRCA-coded mixtures

Variance*	Mixture ID.	Mixture proportions (kg/m^3)						Volume (m^3)	
		Mortar mixture				Foam mixture			
		Eco-hybrid cement	**Water**	**FRCA**	**SA**	**Foaming agent**	**Water****	**Target**	**Actual**
5%	FRCA1	419.4	138.4	38.57	-	1.5	100	1.0	1.00
10%	FRCA2	397.4	131.1	77.16	-	1.5	100	1.0	0.96
15%	FRCA3	375.4	123.9	115.8	-	1.5	100	1.0	0.95
20%	FRCA4	353.4	116.6	154.4	-	1.5	100	1.0	0.93
25%	FRCA5	331.4	109.4	193.0	-	1.5	100	1.0	0.91

* Calculated by mortar volume except F-coded series. In F-coded series, foaming agent content was calculated by water volume in foam mixture.

** Water used in the production of foam mixture, excluding the water in the mortar mixture.

4.3.1. Effect of FRCA content on the physical properties

This part of the research explored the impact of incorporating FRCA on both the fresh and hardened properties of the mixtures. As depicted in Table 4.6, elevating the FRCA ratio from 5% to 25% resulted in a consistent decrease in the average flow diameter, ranging from 262.5 mm to 234.5 mm. This decline in flow diameter continued with each increase in the FRCA ratio, attributed to the considerable water absorption capacity of FRCA, especially in its dry state as employed in this study, which restricts fluidity by absorbing a portion of the mixing water. This finding aligns with previous research indicating that the necessary water content for mixtures steadily rises with increasing RCA ratio [93].

The outcomes illustrated in Figure 4.7 reveal a notable increase in both fresh and dry densities with higher FRCA content. For instance, the fresh density of the FRCA-1 coded mixture with 5% FRCA stood at 0.699 g/cm^3, while subsequent increments of 5%, 7.58%, 11.73%, and 16.17% were observed in the fresh density for every 5% rise in the FRCA content relative to the FRCA-1 mixture. A similar pattern was observed in the dry density of the mixtures. Although an increase in FRCA content typically results in reduced density values due to the material's porous structure and low specific gravity, this series witnessed an increase in densities [35]. This could be attributed to the constant w/b ratio of the mixtures and the reduced quantity of other mixture components when FRCA was used in higher proportions. Additionally, the rough surface and angular shape of FRCA particles were observed to eliminate air bubbles during mixing, decreasing the total volume of the mixture and subsequently increasing density [36, 94, 95]. Moreover, the rise in FRCA content led to the absorption of evaporable water, retained within the system, further augmenting the fresh density of the foam concrete.

Table 4. 6. Flow diameter of FRCA-coded series

Mixture ID.	Flow diameter (mm)
FRCA1	262.5
FRCA2	258.0
FRCA3	246.0
FRCA4	237.0
FRCA5	234.5

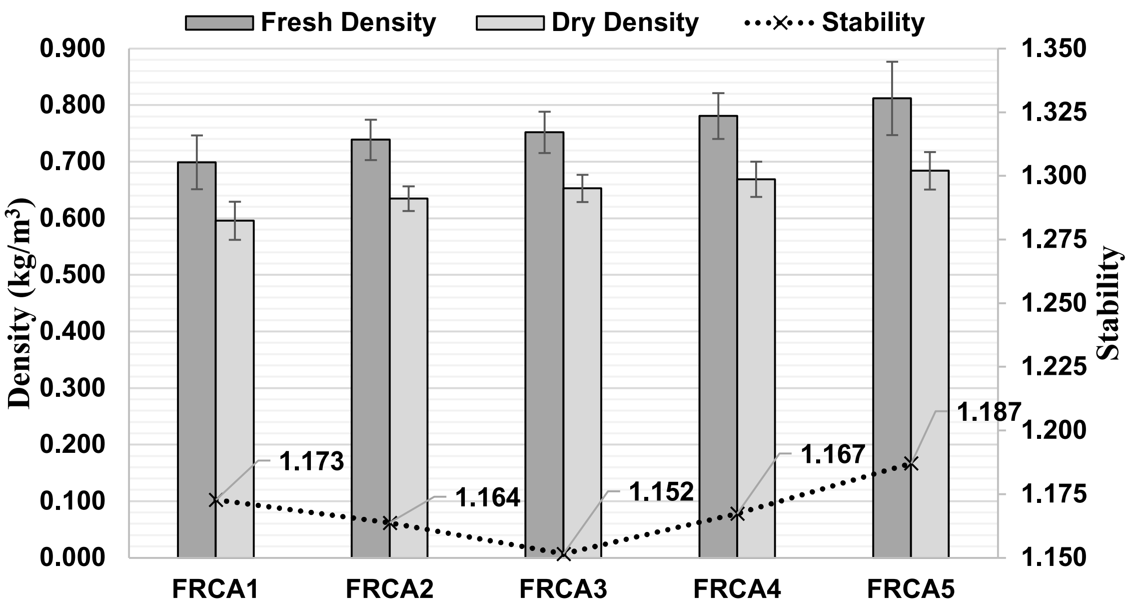

Figure 4. 7. Densities and stabilities of FRCA-coded series

4.3.2. Effect of FRCA content on the mechanical properties

The compressive and flexural strength results for FRCA-coded mixtures are depicted in Figure 11. The investigation revealed a notable decline in strength as the FRCA content increased within the mixture. Specifically, while the FRCA1-coded mixture displayed a compressive strength of 1.39 MPa, each 5% rise in FRCA content led to reductions of 10.07%, 39.56%, 47.91%, and 56.12% in compressive strength compared to the FRCA1-coded mixture (Figure 4.8). This decrease in strength can be attributed to two main factors. Firstly, the increase in FRCA content resulted in a reduction in Eco-hybrid cement content, which is unfavourable for compressive strength. Secondly, higher FRCA content led to the formation of voids, porosity, and microcracks in the matrix, contributing to a decrease in matrix strength [35, 96]. It is widely acknowledged that a major drawback of FRCAs is the formation of weak and microcracked regions due to the development of secondary ITZ between the FRCA and new cement paste, alongside the old ITZ between the original aggregate and old adhered mortar. This was evidenced in a previous SEM analysis [35]. However, the study suggests that utilizing FRCA to its maximum feasible extent is beneficial due to its micro-filler effect [97], which contributes to structural integrity and stability of the matrix. Additionally, the eco-friendly and cost-effective nature of FRCA compared to cement makes its integration into foam concretes highly desirable.

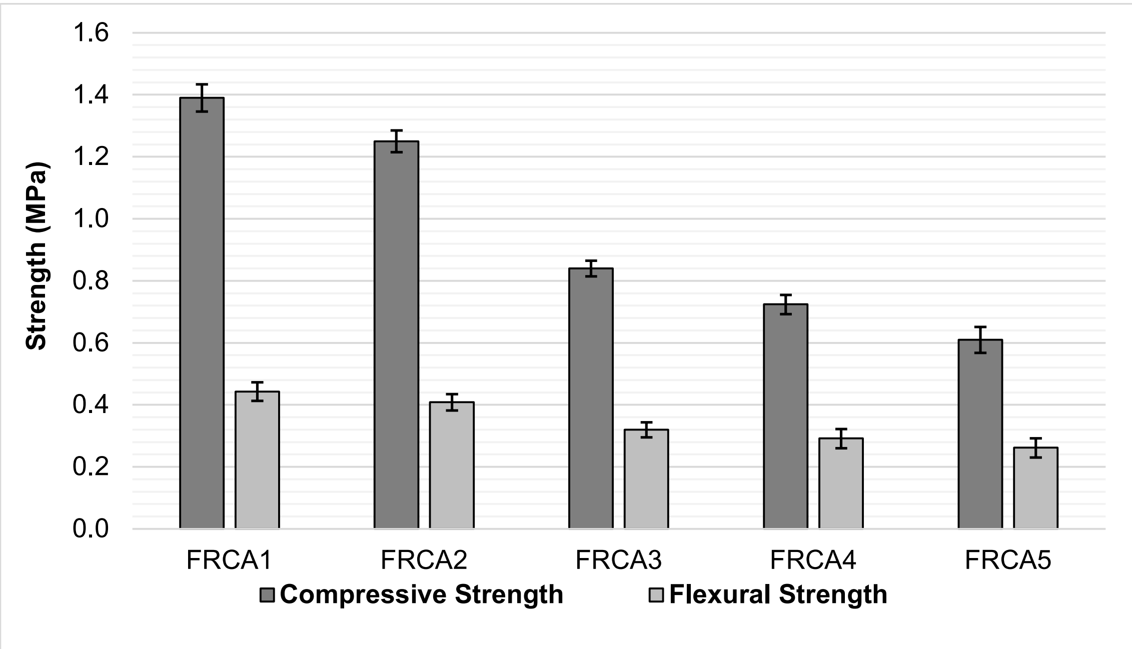

Figure 4. 8. Compressive and flexural strength results of FRCA-coded series

4.4. Optimizing foaming agent content

The series designated as F-coded encompassed five distinct mixture designs featuring varying foaming agent content, including 1.00%, 1.50%, 2.00%, 2.50%, and 3.00%, relative to the foam mixture. These designs are comprehensively presented in Table 4.7.

Table 4. 7. F-coded mixtures

Variance*	Mixture ID.	Mixture proportions (kg/m^3)						Volume (m^3)	
		Mortar mixture				Foam mixture			
		Eco-hybrid cement	Water	FRCA	SA	Foaming agent	Water**	Target	Actual
1.0%	F1	427.1	140.9	129.2	-	1.0	100	1.0	1.01
1.5%	F2	391.5	129.2	118.4	-	1.5	100	1.0	1.02
2.0%	F3	377.2	124.5	114.1	-	2.0	100	1.0	1.00
2.5%	F4	317.5	104.8	96.04	-	2.5	100	1.0	1.00
3.0%	F5	249.6	82.38	75.51	-	3.0	100	1.0	1.00

** Water used in the production of foam mixture, excluding the water in the mortar mixture.

4.4.1 Effect of foaming agent content on the physical properties

This section of the study examined the influence of different foaming agent ratios on the characteristics of lightweight foam concrete. It was determined that this ratio is a critical factor affecting the properties of foam concrete in both its fresh and hardened states. As shown in Table 4.8, the average flow diameters of the mixtures exhibited an increasing trend with the elevation of the foaming agent ratio from 1.0% to 3.0% at 0.5% increments. The increments were 8.95%, 14.54%, 17.67%, and 21.70% relative to the F1-coded mixture, respectively. Notably, the F-5 coded mixture, prepared with a 3.0% foaming agent, demonstrated the highest average flow diameter of 272 mm. These results align with a prior study [98], which indicated that the impact of increased foaming agent on workability diminishes after reaching a certain level. Additionally, in this study, it was observed that the enhancement in workability gradually diminished as the foaming agent ratio increased.

The foaming agent plays a pivotal role in determining the fresh and hardened properties of foam concrete [88]. Inadequate use of the foaming agent cannot achieve desired properties such as lightweight characteristics and thermal conductivity. Conversely, excessive use compromises the structural integrity of the slurry. The parameters of the foaming agent are widely recognized to play a crucial role in regulating the fresh and hardened characteristics of foam concrete. The results depicted in Figure 4.9 indicate a significant decrease in the fresh and dry densities and stability value of the F-coded mixtures with the augmentation of foaming agent content. Specifically, incorporating the foaming agent at rates of 0.5% from 1.0% to 3.0% led to reductions in fresh density by 8.59%, 9.47%, 21.72%, and 35.73% compared to the F1-coded mixture, respectively. Similarly, the dry density values decreased by 11.97%, 13.87%, 28.18%, and 44.53%, respectively. The increased foaming agent ratio results in a higher concentration of air bubbles and voids in the system, significantly affecting the volumes of the mixtures and causing a decline in densities [99, 100]. However, the stability of the mixtures tends to deteriorate with the increasing foaming agent content. The ratio between the fresh and dry densities of the mixtures notably increases as the foaming agent level surpasses 2.0% (F3-coded mixture), leading to a higher susceptibility to degradation. The formation of air bubbles in varying sizes and quantities, along with the heterogeneous nature of the matrix upon the inclusion of a foaming agent in a cementitious slurry, contributes to the formation of weak regions within the matrix [7]. The presence of a high amount of air bubbles in the mixture causes these weak regions to progressively connect and fail to maintain the structural integrity of the sample. Therefore, optimizing the usage rate of the foaming agent is recommended to achieve properties such as the lowest density and thermal conductivity without compromising structural integrity.

Table 4. 8. Flow diameter of F-coded series

Mixture ID.	**Flow diameter (mm)**
F1	223.5
F2	243.5
F3	256.0
F4	263.0
F5	272.0

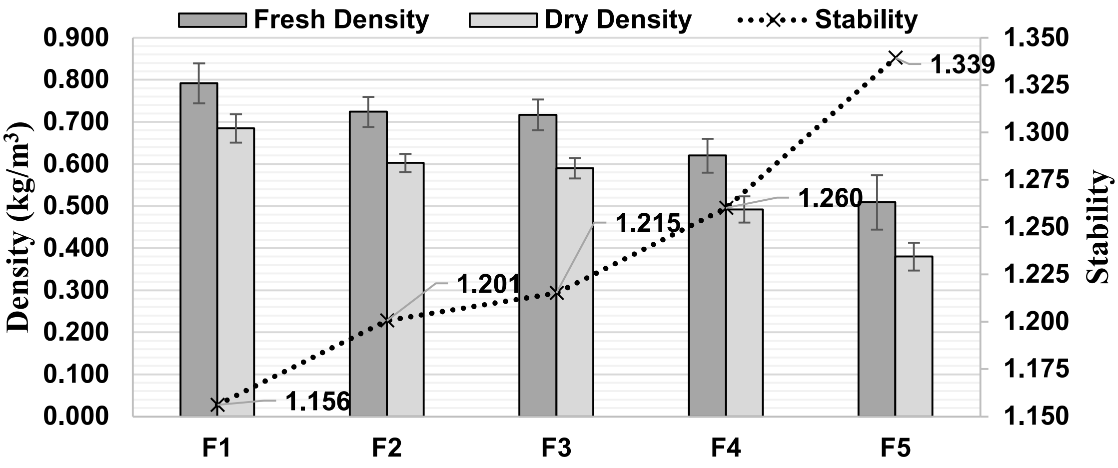

Figure 4. 9. Densities and stabilities of F-coded series

4.4.2. Effect of foaming agent content on the mechanical properties

The compressive and flexural strength test results for the F-coded mixtures are depicted in Figure 4.10. It's clear from the graph that the mechanical properties of the F-coded mixtures experienced a significant decrease as the foaming agent content increased. Specifically, the compressive and flexural strengths of the F1, F2, F3, F4, and F5 coded mixtures, utilizing foaming agent at 1.0%, 1.5%, 2.0%, 2.5%, and 3.0%, respectively, were determined. The compressive strengths were measured as 1.21, 0.93, 0.76, 0.44, and 0.28 MPa, while the flexural strengths were 0.40, 0.36, 0.32, 0.20, and 0.11 MPa, respectively. This decline in mechanical performance can be attributed to the reduction in the volume of solid components, leading to decreased density, stability, and mechanical strength [88]. The introduction of air bubbles into the mixture via the foaming agent has increased porosity, which is known to have an adverse effect on strength [101]. Additionally, the F4 and F5 coded mixtures, which exhibited the lowest strength values throughout the study, also showed signs of low stability, partial fragmentation, and abrasion, as depicted in Figure 4.10.

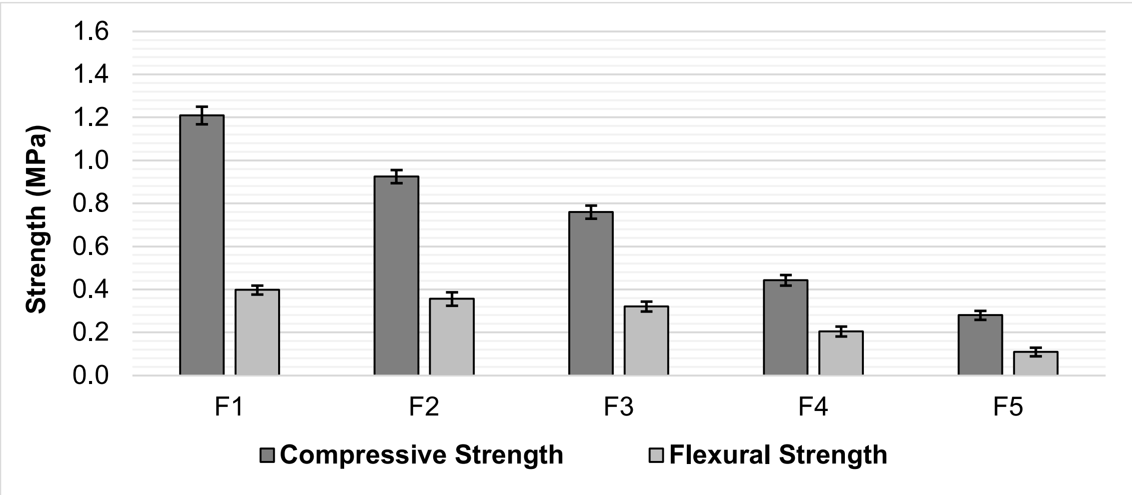

Figure 4. 10. Compressive and flexural strength results of F-coded series

4.5. Optimizing Silica-aerogel content

The fifth series, labeled as SA-coded, included six unique mixture designs, each featuring varying levels of silica-aerogel content, ranging from 0% to 5%. Additionally, within the SA-coded series, there was a base mixture (SA0) formulated based on optimal density, stability, and strength values derived from other series, specifically C4, WB3, and

FRCA3. These specific mixture configurations are elaborated upon in Table 4.9, and photographs of the samples are shown in Figure 4.11.

Figure 4. 11. Panel samples of SA-coded series

Table 4. 9. SA-coded mixtures

Variance*	Mixture ID.	Mixture proportions (kg/m³)						Volume (m^3)	
		Mortar mixture				Foam mixture			
		Eco-hybrid cement	Water	FRCA	SA	Foaming agent	Water**	Target	Actual
0.0%	SA0	376.4	124.2	113.9	-	1.5	100	1.0	0.91
1.0%	SA1	364.2	120.2	110.2	0.70	1.5	100	1.0	0.90
2.0%	SA2	352.0	116.2	106.5	1.40	1.5	100	1.0	0.93
3.0%	SA3	339.8	112.2	102.8	2.10	1.5	100	1.0	0.93
4.0%	SA4	327.6	108.1	99.11	2.80	1.5	100	1.0	0.92
5.0%	SA5	315.4	104.1	95.42	3.50	1.5	100	1.0	1.00

* Calculated by mortar volume except F-coded series. In F-coded series, foaming agent content was calculated by water volume in foam mixture.

** Water used in the production of foam mixture, excluding the water in the mortar mixture.

4.5.1. Effect of silica-aerogel content on the physical properties

This section explores the effects of altering the silica-aerogel ratio, ranging from the reference mixture to 5.0% at 1.0% intervals, on both the fresh and hardened properties of the mixtures, as well as their thermal conductivity properties. Examination of the data in Table 4.10 revealed that the silica-aerogel content had minimal impact on the average flow diameters of the mixtures, which ranged from 245.5 mm to 249.5 mm.

The fresh and dry densities, along with stability values of the SA-coded mixtures, are illustrated in Figure 4.12. The results indicate that as the silica-aerogel content increased from 0.0% to 5.0%, the fresh density values decreased from 0.788 g/cm^3 to 0.620 g/cm^3, and the dry density decreased from 0.619 g/cm^3 to 0.514 g/cm^3. Remarkably, even a small addition of 5.0% (3.5 kg/m^3) silica-aerogel led to an 18.58% reduction in dry density. It's well known that achieving optimal thermal and acoustic performance in lightweight foam concretes requires careful optimization of porous structure and density while maintaining structural integrity. Typically, lightweight aggregates like expanded perlite and pumice are used alongside foaming agents to achieve this optimization, but their high water absorption capacities pose challenges at high utilization rates [102, 103]. The results demonstrate that silica-aerogel can effectively reduce density to enhance thermal and acoustic performance, even at very low rates, thanks to its hollow structure and extremely low density compared to other mixture components [104]. Interestingly, the stability values of the mixtures were not significantly impacted by varying silica-aerogel utilization rates. A stability value close to 1.0 suggests minimal shrinkage, abrasion, or fragmentation issues, indicating that the addition of silica-aerogel holds promise for reducing density values without adverse effects. Notably, the SA-5 coded mixture showed slightly lower stability compared to other mixtures.

Table 4. 10. Flow diameter of SA-coded series

Mixture ID.	**Flow diameter (mm)**
SA0	245.5
SA1	247.5
SA2	247.0
SA3	249.5
SA4	247.0
SA5	247.5

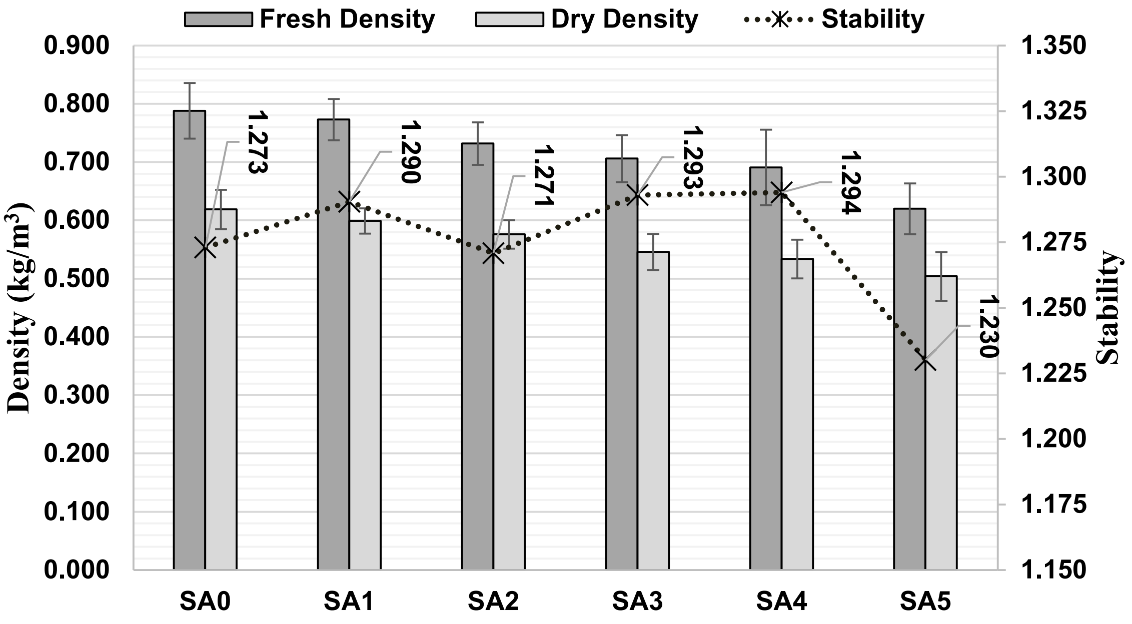

Figure 4. 12. Densities and stabilities of SA-coded series

4.5.2. Effect of silica-aoreogel content on the mechanical properties

Figure 4.13 depicts the compressive and flexural strength results of the SA-coded mixtures. The data showed that the SA0-coded reference mixture, without silica-aerogel, had a compressive strength of 0.960 MPa and a flexural strength of 0.384 MPa. With a 1.0% increase in silica-aerogel content from 0% to 5.0%, there were decreases of 6.77%, 9.69%, 11.46%, 13.33%, and 1% in compressive strength, respectively, compared to the SA0-coded mixture. Similarly, the flexural strengths decreased by 12.36%, 27.52%, 32.03%, 34.64%, and 39.06%, respectively, in comparison to the SA0-coded mixture. Unlike other parameters examined in this study, the concentration of silica-aerogel did not notably impact the strength values of the mixtures. Several studies in the literature have suggested that the compressive strength of mixtures containing silica-aerogel is significantly reduced due to the inherently low strength of silica-aerogel, particularly at higher utilization rates [50, 105]. Furthermore, the data presented in Figure 4.13 indicated that mixtures with lower silica-aerogel content (SA1 and SA2) exhibited more substantial decreases in compressive strength compared to those with higher silica-aerogel content (SA3, SA4, SA5). However, the compressive strength of the latter mixtures reached negligible levels and showed a stabilization trend. This phenomenon, as suggested by previous studies, is attributed to the low adhesion of silica-aerogel and cementitious components in mixtures with low silica-aerogel content, whereas the stabilization of compressive strength drops at higher silica-aerogel incorporation ratios is linked to a reduction in the quantity of strength-contributing components in the system [106].

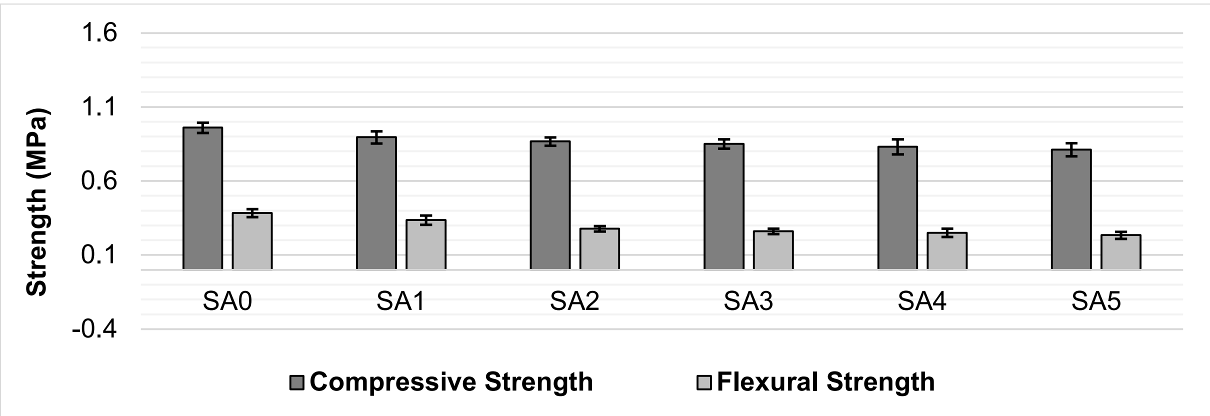

Figure 4. 13. Compressive and flexural strength results of SA-coded series

4.6. Thermal Conductivity

The objective of this study was to assess how varying silica-aerogel ratios affect the thermal properties of mixtures. Thermal conductivity analysis was conducted solely on the SA-coded panel specimens. The results, presented in Figure 4.14, revealed a decrease in thermal conductivity values as the silica-aerogel ratios increased. For instance, after 14 days, the SA0, SA1, SA2, SA3, SA4, and SA5 coded mixtures exhibited thermal conductivity values of 0.172, 0.152, 0.134, 0.127, 0.089, and 0.061 W/mK, respectively. Similarly, after 28 days, these values were recorded as 0.149, 0.140, 0.123, 0.115, 0.077, and 0.049 W/mK. Notably, the mixture containing 5.0% silica-aerogel (SA5) showed a significant 66.98% reduction in thermal conductivity compared to the SA0-coded mixture after 28 days. Previous research has highlighted the effectiveness of silica-aerogel in reducing thermal conductivity values due to its unique nano-porous structure, which enhances the material's overall porosity [105, 107, 108]. The nanopores of silica-aerogel confine air molecules within a small nano-sized space, leading to an increased mean free path of air molecules and a subsequent reduction in thermal gas conductivity (known as the Knudsen effect) [109, 110]. The findings of this study align with these explanations, as increasing the silica-aerogel content in the SA-coded series resulted in a significant decrease in thermal conductivity values compared to density values. Thus, materials like silica-aerogel, which exert considerable influence at the nano-scale, can effectively achieve desired thermal and acoustic performances in foam concretes, despite the close relationship between density and thermal conductivity.

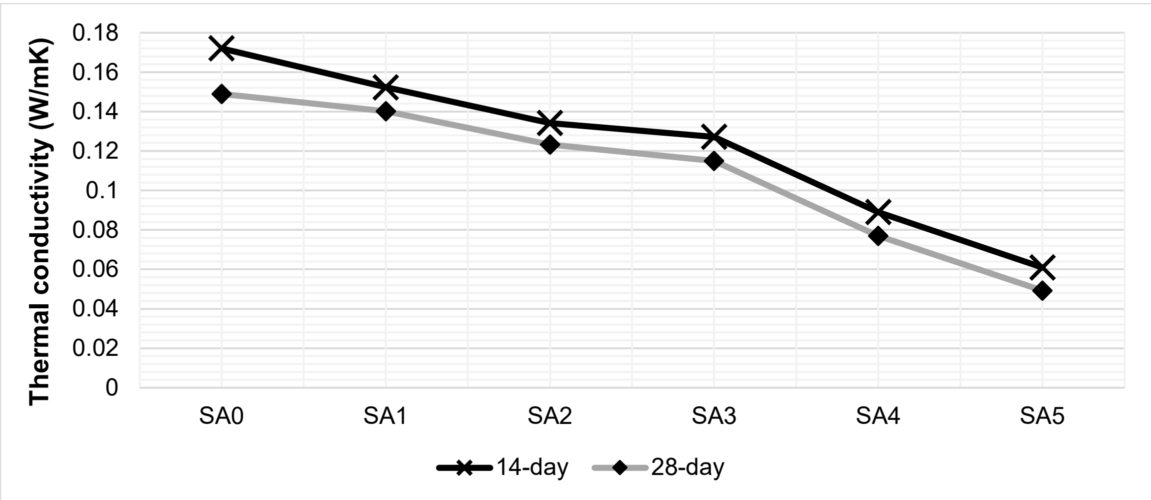

Figure 4. 14. Thermal conductivity performances of SA coded series for 14 and 28 days

4.7. Comparison of the final product with the control mixture

A control mix was created to serve as a benchmark against the SA0 mix, which demonstrated the most favourable fresh and mechanical characteristics in the study. The control mix utilised only Ordinary Portland cement 42.5R and normal aggregates of a similar size to those in the SA0 mix, rather than the recycled concrete aggregates and Eco-hybrid cement employed in SA0. Test samples for both the control and SA0 mixes are depicted in Figure 4.15.

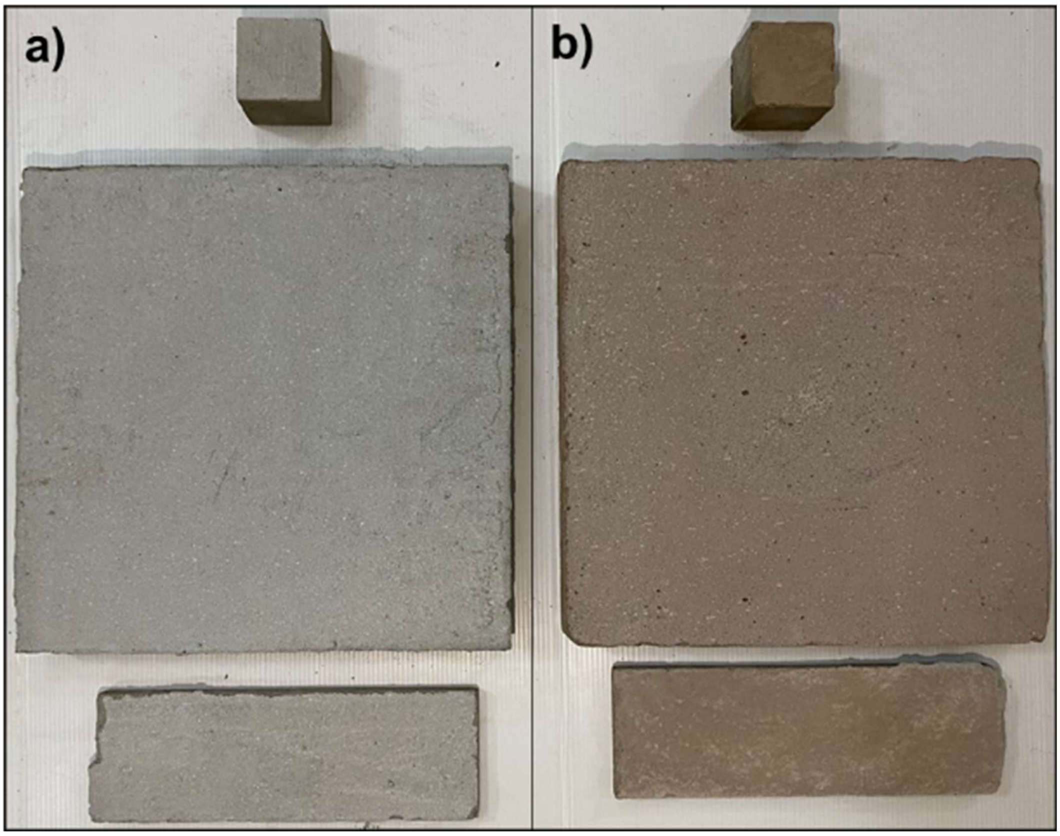

Figure 4. 15. Visual images of the specimens, a) control mixture; b) SA0-coded mixture

Table 4.11. presents the fresh, mechanical, and thermal attributes of both mixtures. The analysis of the fresh properties revealed that the control mix exhibited higher fresh and dry densities, with values of 0.864 g/cm³ and 0.705 g/cm³, respectively. These values were 9.64% and 13.89% higher than those observed in the SA0 mix. This discrepancy is primarily attributable to the lighter weight of the recycled concrete aggregates, which have old mortar residue contributing to their reduced density. Consequently, mixes utilising normal aggregates are denser than those employing recycled materials. The lighter weight of the CDW materials in comparison to Portland cement also leads to the

lower density of the Eco-hybrid cement-based SA0 mix. The control mix was also found to be more fluid than the SA0 mix, likely due to the absorption of water by the recycled concrete aggregates during mixing, which reduces the mix's workability. In mechanical terms, the control mix demonstrated significantly stronger performance with compressive and flexural strengths of 1.326 MPa and 0.472 MPa, respectively. This superior performance is largely due to the more effective binding capabilities of Portland cement compared to Eco-hybrid cement. However, the high aluminosilicate content in the CDW materials used in the Eco-hybrid cement may enhance strength over time through pozzolanic reactions. The less dense structure of the recycled aggregates contributes to the SA0 mix's weaker mechanical properties. Finally, the thermal conductivity was found to be higher in the control mix, with a value of 0.819 W/mK, in comparison to the SA0 mix. This increase can be attributed to the denser and more uniform matrix of the Portland cement-based control mix, which results in a lower thermal insulation performance. Conversely, the SA0 mix benefits thermally from the porous nature of the recycled aggregates.

Table 4. 11. Properties of control and SA0-coded mixtures

Properties	**Control**	**SA0**
Fresh density (g/cm^3)	0.864	0.788
Dry density (g/cm^3)	0.705	0.619
Flow diameter (mm)	249.0	245.5
Compressive strength (MPa) – 28d	1.326	0.960
Flexural strength (MPa) – 28d	0.472	0.384
Thermal conductivity (W/mK) – 14d	0.189	0.172

4.8. Microstructural characterization

4.8.1. Scanning electron microscopy and Energy-dispersive X-ray spectroscopy analysis

In this section, a microstructural examination was performed on the SA0, SA3, and SA5 coded mixtures using scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX) to observe their matrix properties, pore structure, and atomic distributions. These mixtures were chosen based on their thermal conductivity values, with SA5 having the lowest, SA3 exhibiting medium, and SA0 showing the highest thermal conductivity value. SEM micrographs of the SA0, SA3, and SA5 coded mixtures, depicted in Figures 4.16, 4.17, and 4.18, respectively, revealed matrices containing various sizes of open and closed holes, resembling hive-like structures [48]. Figure 4.17 displayed generally spherical pores of smaller size within the matrix, while Figure 4.16 showed less homogeneous pore distributions, with some regions lacking pores in the cementitious gel structures. Figure 4.18 exhibited large and randomly shaped pores and cavities of varying sizes and distributions within the cementitious gel structures. These observations align with prior research indicating that as sample density increases, pores tend to become smaller and more spherical [111].

Additionally, mapping and point energy-dispersive X-ray spectroscopy (EDX) analyses were conducted on the SA5-coded mixture, presented in Figure 4.19 and 4.20, respectively. The results revealed that the major atomic structures were primarily composed of calcium oxide and silicon oxide, with a minor presence of iron oxide. The relatively high silicon oxide content in CDW materials within Eco-hybrid cement led to a relatively high silicon content in the EDX analysis, differing from the characteristic of traditional Portland cement. Mapping analysis showed homogeneous distribution of different types of oxides, although some regions exhibited clustering of silicon (indicated by the green hue), possibly related to silica-aerogel aggregation. Nonetheless, based on both thermal conductivity and mapping EDX analysis results, it can be inferred that silica-aerogel is generally distributed homogeneously.

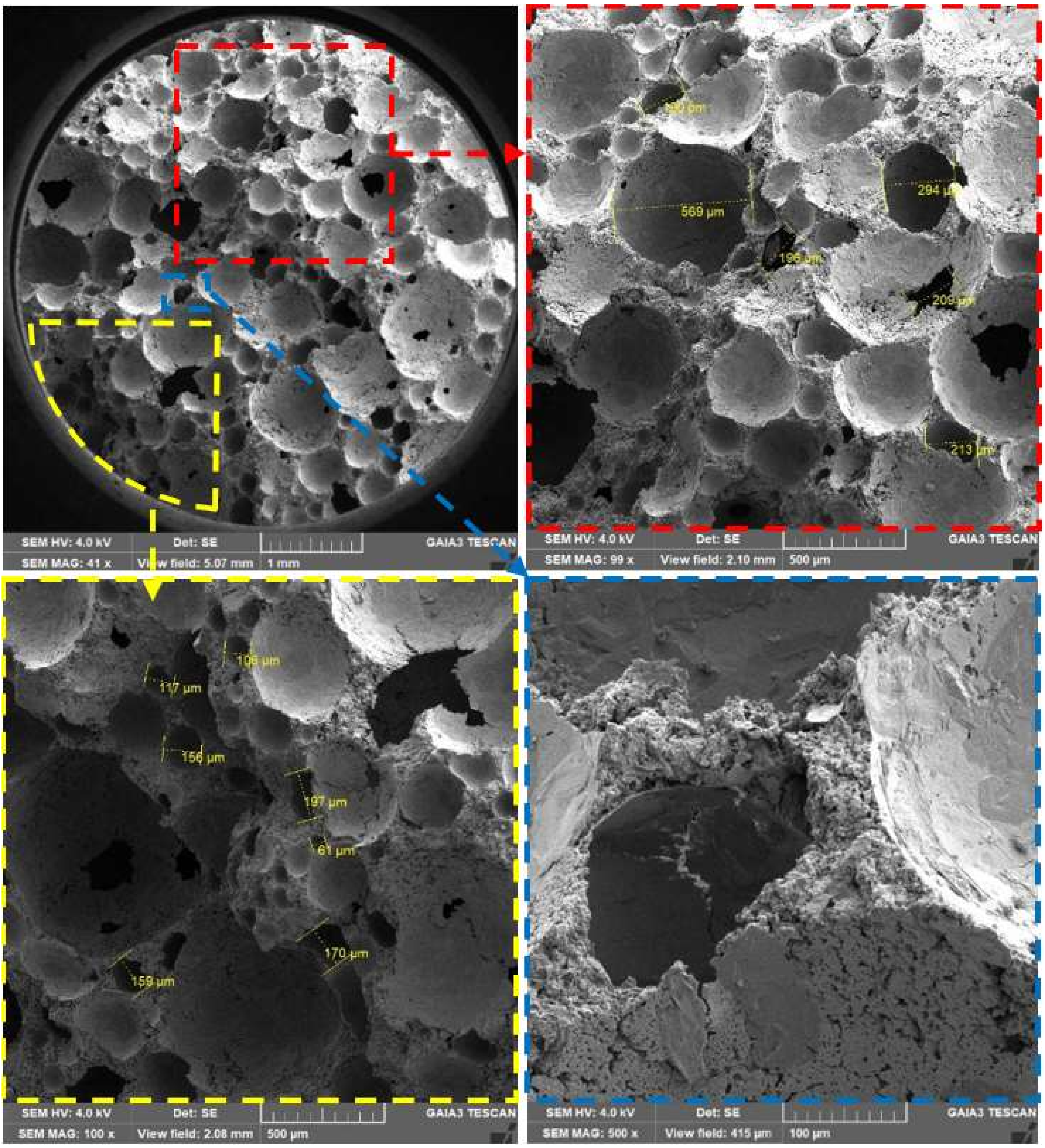

Figure 4. 16. SEM micrographs of SA0-coded mixture

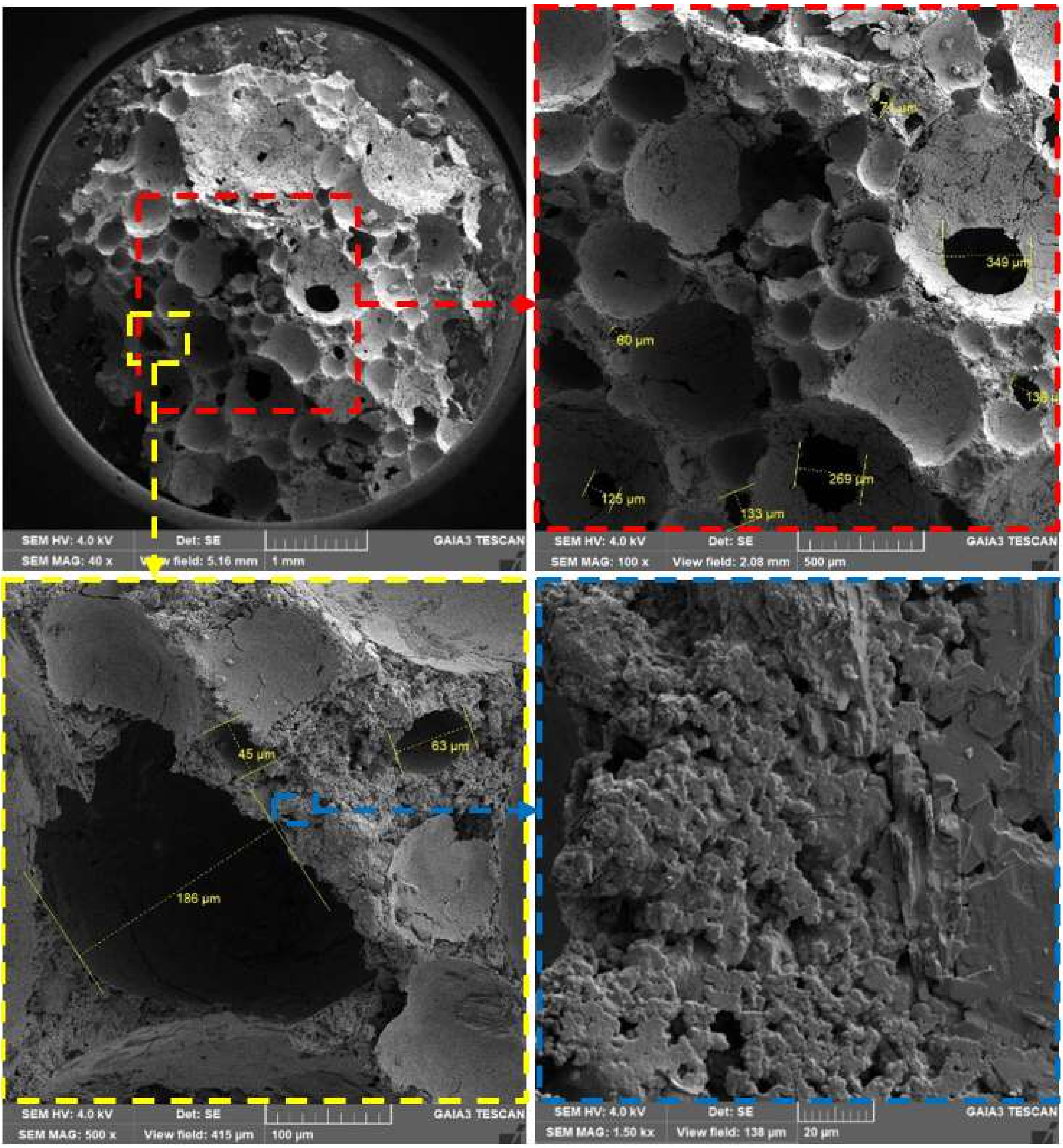

Figure 4. 17. SEM micrographs of SA3-coded mixture

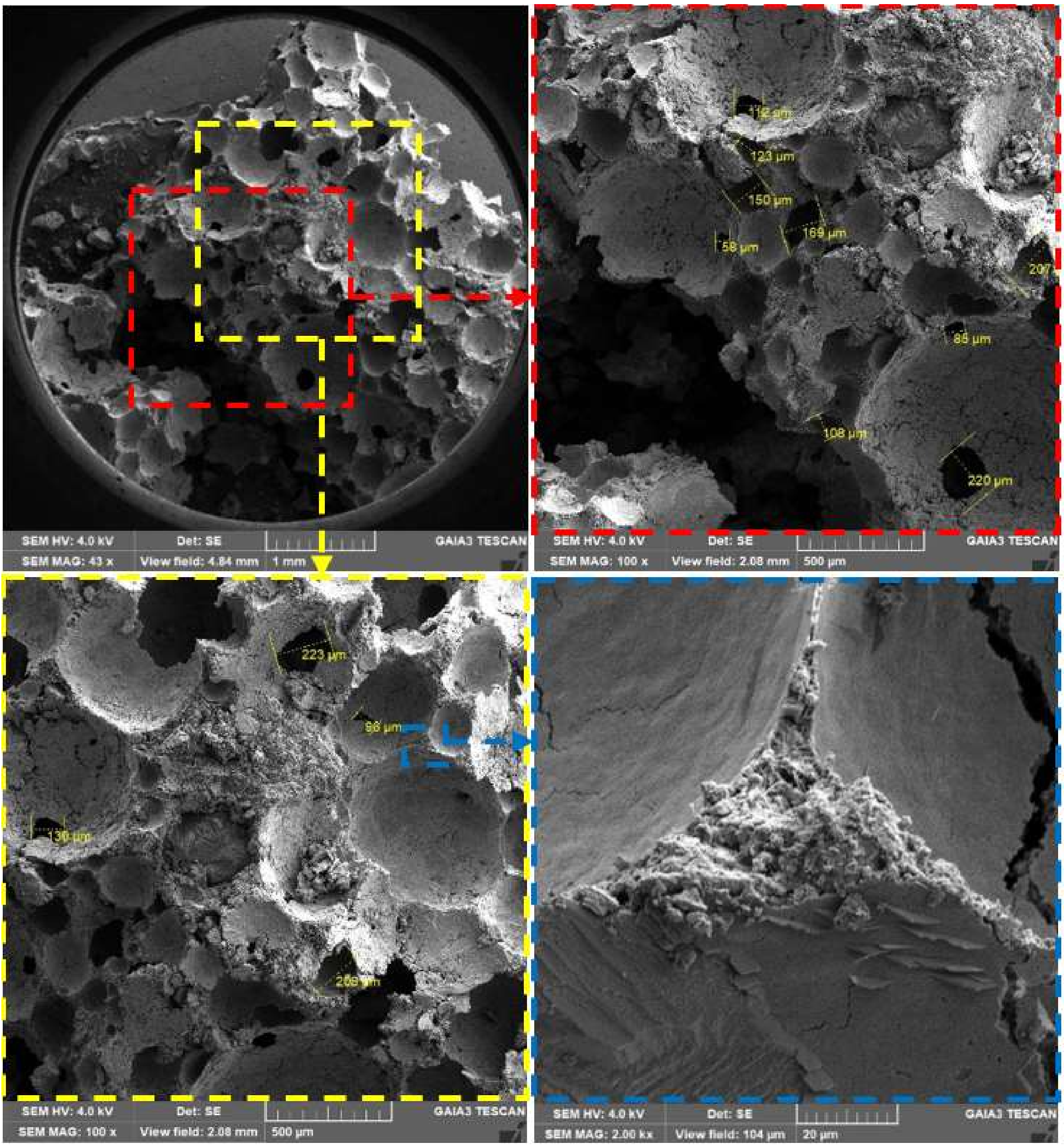

Figure 4. 18. SEM micrographs of SA5-coded mixture

The investigation encompassed mapping and point energy-dispersive X-ray spectroscopy (EDX) analyses of the SA5-coded mixture, showcased in Figure 4.19 and 4.20, respectively. Findings revealed that the primary atomic constituents consisted of calcium oxide and silicon oxide, with a minor presence of iron oxide. The relatively elevated silicon oxide content stemming from CDW materials in Eco-hybrid cement led to a relatively higher silicon content in the EDX analysis, deviating from the characteristic composition of traditional Portland cement. Mapping analysis depicted the homogeneous distribution of various oxide types, although some regions exhibited clustering of silicon (as indicated by the green hue), potentially associated with silica-aerogel aggregation. Overall, it can be inferred from both the thermal conductivity and mapping EDX analyses that silica-aerogel is generally distributed uniformly within the mixture.

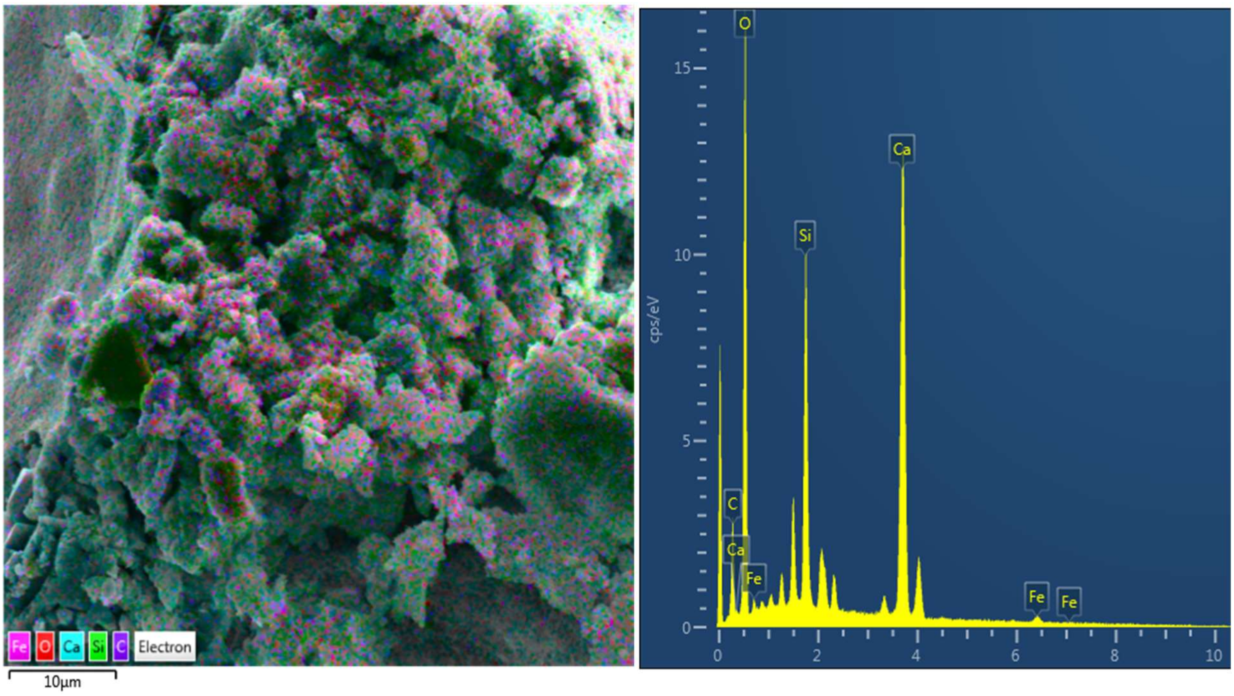

Figure 4. 19. EDX mapping analysis of SA5-coded mixture

The findings from the point EDX analysis for various regions of the SA5 coded mixture are illustrated in Figure 4.20. Examination of points 2, 4, 5, and 6 indicated a balanced distribution of calcium and silicon oxides, indicating the presence of a cementitious gel structure. In contrast, point 3 exhibited a notably high silicon oxide level, suggesting the presence of silica-aerogel aggregation. Point 7 displayed a heightened calcium oxide level, possibly due to the aggregation of FRCA with high calcium content and low silica-aerogel content. In foam concrete production, procedures such as mixing and vibration are often carefully controlled to preserve air bubbles, yet this can lead to uneven dispersion of matrix products and pores, potentially impacting localized insulation and mechanical performance [112]. However, the analysis depicted in Figure 4.20 suggests that, overall, the matrix products were uniformly dispersed, implying minimal impact on mechanical and insulating performance.

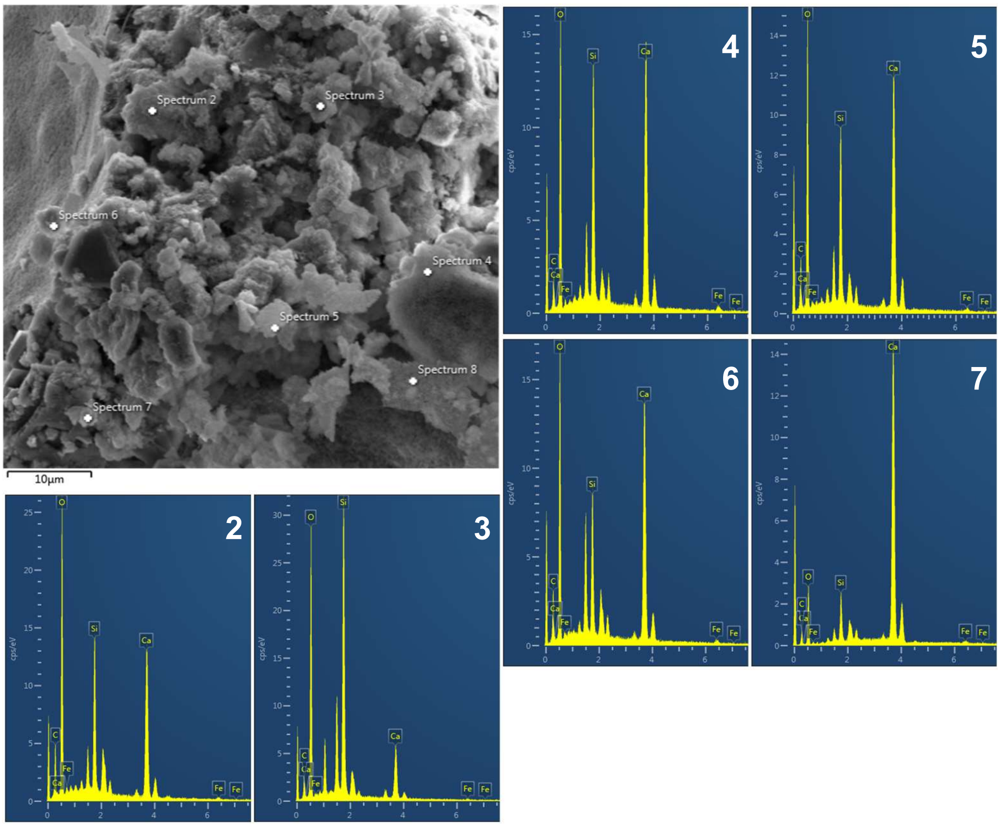

Figure 4. 20. EDX mapping analysis of SA5-coded mixture

4.8.2. Micro-computed tomography analysis

A micro-CT analysis was conducted on SA0-, SA3-, and SA5-coded mixtures to evaluate their pore-related characteristics. Table 4.12 displays the values for open, closed, and total porosity of the specimens, along with their total pore space volume. Results indicated that the SA3-coded mixture exhibited the highest total porosity among the three, at 79.07%. Furthermore, the total pore space volumes for the SA0, SA3, and SA5-coded mixtures were measured at 1006×109, 727×109, and 940×109 µm³, respectively. Interestingly, despite the SA5-coded mixture demonstrating the lowest density and superior thermal conductivity performance, it did not exhibit the highest porosity. This could be attributed to the substantial dosage of silica-aerogel used in the SA5-coded mixture. While silica-aerogel boasts a low weight-to-volume ratio due to its highly porous particle structure, its presence in nanostructured form within the matrix can reduce the overall porosity. This phenomenon was elucidated in a study [53], suggesting that the use of nanoscale silica-aerogel leads to better packing within the matrix, resulting in a more compact microstructure. Additionally, the lack of correlation between the total volume of pore space of the mixtures may stem from differences in sample dimensions and volume during testing.

Table 4. 12. Porosity and total volume of pore space of the SA0, SA3 and SA5-coded mixtures

Mixture ID	**Open porosity (%)**	**Closed porosity (%)**	**Total porosity (%)**	**Total volume of pore space ($\times 10^9$ µm^3)**
SA-0	67.30	0.12	67.42	1006
SA-3	79.04	0.17	79.21	727.0
SA-5	63.05	0.27	63.32	940.0

Micro-CT analysis was performed on SA0-, SA3-, and SA5-coded mixtures to evaluate their pore-related characteristics. Data analysis was conducted using images obtained from CTAn and CTvox software. The findings, depicted in Figure 4.21 and Figure 4.22, indicate that the SA0-coded mixture possessed smaller, mostly spherical pores with higher connectivity. In contrast, the SA3 and SA5-coded mixtures exhibited larger, randomly shaped pores with lower connectivity. The reduced connectivity of pores is crucial for achieving desired thermal and acoustic properties. Furthermore, Figure 4.23. illustrates that the SA0-coded mixture had the highest proportion of pores smaller than 100 µm, while the SA5-coded mixture had the lowest. For pore sizes exceeding 100 µm, the SA5-coded mixture displayed a relatively uniform distribution without significant peak development. However, heterogeneous pore size distributions were found to adversely affect thermal conductivity behavior, with increased porosity leading to a notable reduction in foam concrete's thermal conductivity, consistent with findings from prior studies [113].

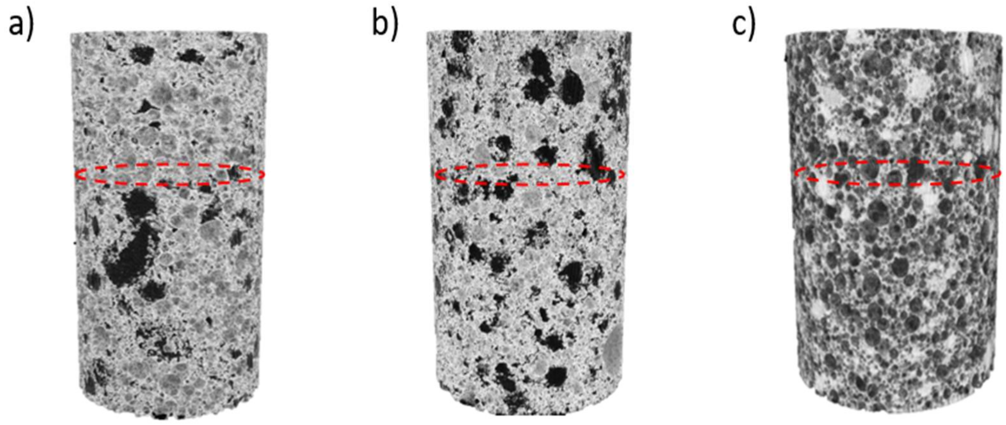

Figure 4. 21. 3D images acquired from micro-CT analysis of the mixture a) SA0; b) SA3 and c) SA5-coded mixture

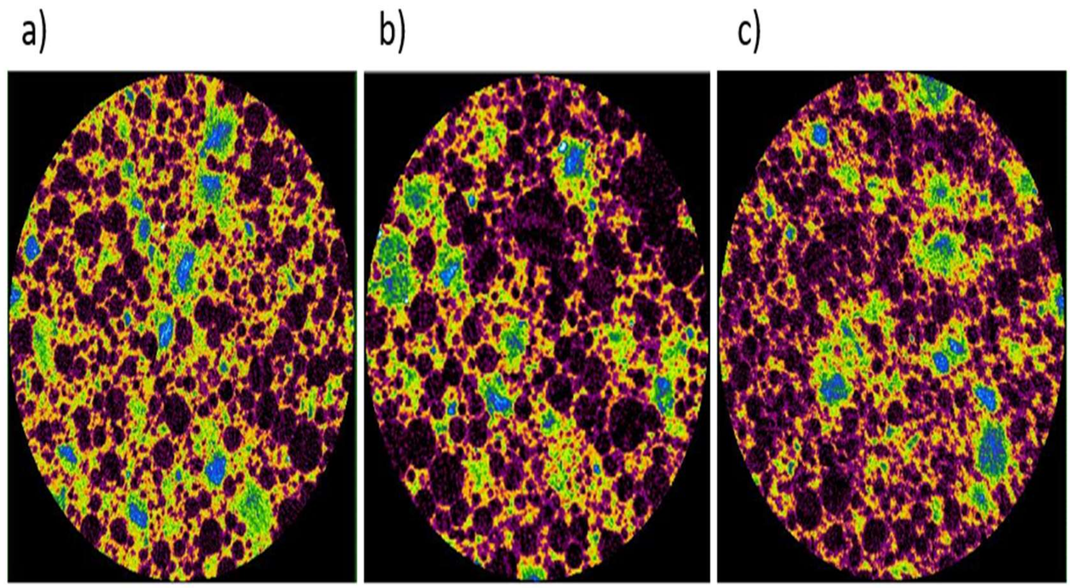

Figure 4. 22. Sectional images acquired from micro-CT analysis of the mixtures, a) SA0; b) SA3 and c) SA5-coded mixture (as the density value increases, the colours follow the order of black-purple-yellow-green-blue, respectively).

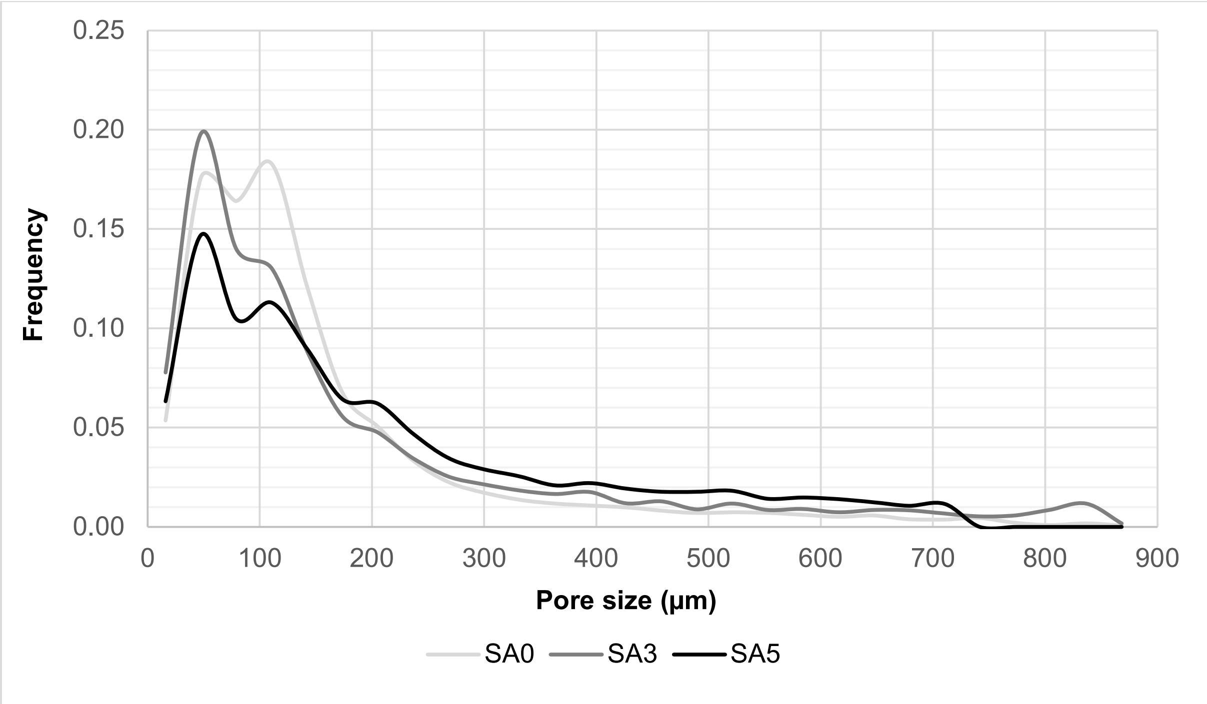

Figure 4. 23. Pore size distribution of the SA0, SA3 and SA5-coded mixtures

5.CONCLUSION

The present investigation aimed to analyze fresh, hardened, and microstructural characteristics of ultra-lightweight green foam concretes. The concretes were prepared using a novel Eco-hybrid cement, FRCA completely derived from CDW, and silica-aerogel. Several parameters such as the quantity of Eco-hybrid cement, FRCA, water-to-binder ratio (w/b), foaming agent, and silica-aerogel were modified to examine their influence on the performance characteristics of the mixtures including fresh and dry densities, stability, flowability, compressive and flexural strength, and thermal properties. Further, microstructural analyses were examined using scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM/EDX) and micro-computed tomography (micro-CT) analysis for detailed evaluation. Based on the results, several significant findings were drawn as follows:

- The fresh properties of ultra-lightweight green foam concrete were primarily influenced by the content of FRCA and foam condition. The increase in FRCA content led to a significant increase in density values and a decrease in flowability of the mixtures. Moreover, reducing the FRCA content in the mixtures and increasing the water content generally resulted in weaker stability.
- The mechanical properties of ultra-lightweight green foam concrete were mainly affected by the content of foaming agent and Eco-hybrid cement. Increasing the amount of Eco-hybrid cement and decreasing the quantity of foaming agent had a significant positive impact on the compressive and flexural strength of the mixtures.
- The fresh and hardened properties of the mixtures were not significantly affected by varying amounts of silica-aerogel. However, the thermal performance of the mixtures was greatly influenced by the amount of silica-aerogel used. The mixture containing 5.0% silica-aerogel showed the best thermal conductivity performance compared to the other mixtures containing silica-aerogel in ratios ranging from 1.0% to 5.0%.
- Based on the SEM/EDX and micro-CT analyses, it was found that the mixtures exhibited a highly porous microstructure characterized by pores of varying sizes and distributions. The pore size distribution and interconnectivity were identified

as crucial factors affecting properties such as density, compressive strength, and, in particular, thermal performance of the mixtures.

- The control mixture, utilizing ordinary Portland cement and normal aggregates, exhibited higher density and strength values compared to the SA0 mixture. The lower density of RCAs, due to the presence of old adhered mortar residue, and the lower density of CDW materials in the Eco-hybrid cement contributed to the lower density values of the SA0 mixture. The porous structure of RCA also led to a lower mechanical performance in the SA0 mixture compared to the control mixture, while the control mixture had higher thermal conductivity due to its denser and more homogeneous matrix. As a result, the use of a high amount of CDW-based materials did not have a significant impact on the mechanical performance of the final products, and the structural integrity was not compromised which is one of the main objectives to develop non-structural panels. On the other hand, it led to an improvement in their thermal insulation performance.

To put the research findings into numbers, an ultra-lightweight green foam concrete with a dry density of 0.514 g/cm^3, compressive strength of 0.812 MPa, flexural strength of 0.234 MPa, and thermal conductivity of 0.049 W/mK has been successfully developed. Considering the fact that the recycling/upcycling of CDW and its participation in the circular economy model is one of the five priority targets of the European Action Plan, the development of circular building insulation materials to ensure long-term sustainability and promote circular thinking is highly encouraged by the outcomes of this study. It would be beneficial to conduct future research on the long-term durability properties of foam concretes containing high amounts of CDW against chemical agents as well as life cycle environmental and cost analyses to reveal their environmental and financial advantages over market-ready products.

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