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Assessment of sustainability Aspects of Recycled Aggregate with supplementary Cementitious Materials

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Abstract

The sustainability of engineering products has evolved from being optional to an essential requirement. This research investigates the effects of using 20% fly ash (FA) and or 12% silica fume (SF) as replacements for cement in the production of recycled aggregate concrete. The study was carried out in two phases: the evaluation phase and the analysis phase. During the evaluation phase, laboratory tests and data collection were conducted to assess the mechanical properties, environmental impact, and production costs of ten different concrete mixtures. In the analysis phase, three multi-criteria decision-making methods (EDAS, VIKOR, and TOPSIS) were applied to determine the most effective and sustainable concrete mixture. The main findings revealed that using up to 70% recycled concrete aggregate combined with an optimal mixture of 20% FA and 12% SF results in high- quality, eco-friendly, and cost-efficient concrete. This study evaluates the environmental effects of incorporating supplementary cementitious materials (SCMs) .It also examines the structural performance of using construction and demolition waste as a partial replacement for natural aggregates in concrete, focusing on compressive strength and durability. Findings indicate that the inclusion of SCMs and ENMs lowers the global warming impact (GWI) and cumulative energy demand (CED) of concrete production without compromising strength and durability. In some instances, it even improves both durability and strength. However, there is a tradeoff between durability and strength enhancement with the use of reengineered by-products, which leads to an increase in GWI and CED. Although they yield nearly the same GWI and CED as ordinary Portland cement concrete, optimizing the use of recycled aggregates as a partial substitute for natural aggregates can reduce the reliance on virgin materials.

Keywords: Supplementary cementitious materials, Recycled aggregate; building material, Fly Ash, sustainable concrete, Silica fume, EDAS, VIKOR, TOPSIS

Introduction

Due to rapid industrial growth and unsustainable practices worldwide in recent decades, sustainable development has become a critical issue today. The construction and building materials industry plays a major role in the creation of structures, particularly in areas where concrete is the primary building material. Concrete has been regarded as the most commonly used material for the past three centuries. As a result, recycled aggregate concrete (RC) is highly beneficial, contributing to the conservation of environmental resources, reduction of carbon emissions, and the effective utilization of demolition waste, leading to lower energy consumption. Each year, large quantities of construction material waste are generated, posing a threat to the environment, consuming significant energy, and incurring substantial costs for processing.

Typically, 60–70% of concrete consists of aggregate, which is a key component for the beneficial reuse and recycling of concrete. Since the early 1980s, European nations have been exploring the use of recycled concrete aggregate (RA) in new reinforced concrete (RC) structures. Numerous studies have shown that the use of RA is sustainable, cost-effective, and widely accepted. The physical and mechanical properties of RC can be influenced by the characteristics of RA, which differ from natural aggregate (NA) due to the residual mortar from

the original concrete. The lower mechanical strength of RA impacts the strength properties of RC. The compressive strength of RC is generally similar to that of conventional concrete when the replacement proportion is small (<25%). However, as the proportion of RA in concrete increases, the strength of the concrete significantly decreases, with the strength diminishing as the replacement rises from 25% to 100%. The highwater absorption of recycled aggregate (RA) and its weak bond with the cement paste lead to a decrease in the strength of recycled concrete (RC). However, adjusting the water-to-cement ratio, using the correct type and dosage of superplasticizer, increasing the cement content, and incorporating supplementary cementitious materials (SCMs) can help compensate for the loss of strength. The use of fly ash (FA) and/or silica fume (SF) can enhance both the mechanical and durability properties of RC. FA improves the workability of RC, while SF strengthens its microstructure due to its fine particle size and large surface area. S.C. Kou et al. conducted experiments with RC containing varying amounts of FA as a cement replacement and found that 25% FA is the optimal proportion for producing RC. Additionally, S.C. Kou et al. discovered that using approximately 10% SF enhances the strength of RC, and the RA replacement ratio does not affect the amount of SF required to improve strength. A summary of previous studies on RC incorporating FA and/or SF is presented in Table 1. Due to the broad range of concrete applications and advancements in technology, each concrete mix may vary depending on customer and project requirements. Nevertheless, achieving sustainable concrete requires considering all aspects. Regarding environmental impact, carbon dioxide (CO2) emissions are a critical issue that must be addressed, as a significant amount of CO2 is emitted during the production and transportation of building materials. RC can help reduce CO2 emissions by recycling conventional concrete rubble into new concrete products. Therefore, sustainable performance, which is the balance between quality and environmental factors, can be achieved by evaluating experimental concrete performance, environmental impact, and economic factors. Multi-Criteria Decision-Making (MCDM) techniques can consider multiple criteria to provide the best concrete option that meets quality, environmental, and resource requirements.

The challenges related to the potential expansion of supplementary cementitious materials (SCMs), such as calcareous fly ash, wood ash, or activated copper tailings [8], stem from their physical and chemical characteristics, which can, in turn, enhance certain properties of concrete (performance enhancement). Indeed, the use of SCMs leads to noticeable differences in the microstructure of cement and concrete, including a reduction in the overall volume of open pores in the hardened cement paste and the interface between the paste and aggregate particles. This results in improved performance of cement-based composites, particularly in terms of durability and resistance to harsh environments (such as carbonation, chloride ion presence, sulphates, etc.), by, for example, enhancing water tightness.

Therefore, several research topics related to supplementary cementitious materials (SCMs) are explored and thoroughly discussed through both research papers and comprehensive reviews. The articles included in this Special Issue address the design, testing, and application of various types of SCMs in concrete. The findings from research conducted by over 45 international universities and scientific institutions highlight the significant interest in the SCM subject. In fact, these studies promote the adoption of new, more environmentally sustainable construction materials with enhanced physical and mechanical properties for use in building engineering.

The primary objective of this study is to investigate and offer a clearer understanding of the mechanical properties, environmental impact, and production costs of recycled concrete (RC) containing 20% fly ash (FA) and/or 12% silica fume (SF). Simultaneously, a sustainability framework is developed for the concrete produced by utilizing three Multi- Criteria Decision-Making (MCDM) methods: EDAS, VIKOR, and TOPSIS. To accomplish this, six criteria were evaluated for ten different concrete mixtures, including compressive strength, flexural strength, splitting strength, material volume, CO2 emissions, and the cost of materials used.

Literature review

1.Srikonda Ramesh et al. in their study demonstrated that nearly 2 million buildings have been constructed in India, excluding offices, commercial, and industrial structures, with demand and supply steadily increasing each year. In terms of environmental impact, fossil fuels could become a major contributor to greenhouse gas emissions, thereby increasing costs. The key phases from an energy intensity perspective include: (a) raw material extraction; (b) preparation and manufacturing; (c) transportation, with energy consumption for

transport varying by location. However, studies havehighlighted that transporting materials typically requires 1 MJ per tonne per kilometer (diesel), a factor that can be adjusted based on specific location analysis. Furthermore, energy consumption figures for various materials, as 6mm glazing, and fly ash bricks kg greenhouse gas emissions, and the loss of fertile land. In brick work façade products are in Kolkata brick size of 230x115x65mm later Indian standard brick size is 190x90x90 now the traditional clay bricks no longer sustainable in Kolkata because coal fixed power plant. In 2003 central government India notified located figures for various materials have been considered for energy evaluation, including 10% calcined gypsum, steel (42 MJ/kg), aluminum (236.8 MJ/kg), glass (25.8 MJ/kg), burnt clay bricks (4.25 MJ), and hollow blocks (12.3–15 MJ), among others. These materials are examined in terms of their energy consumption for selecting appropriate options with respect to energy savings and sustainable development. The concept of advanced and innovative building materials refers to the production of embodied energy, as discussed by Mullick (1992), using industrial waste materials based on their availability and sources for efficient utilization in the construction industry. Kumar et al. (1998) further elaborated on energy conservation and savings achieved by using fly ash-based sand-lime bricks, hollow blocks, and lime-gypsum bricks. Therefore, it is vital to explore various methods of conserving valuable conventional energy, considering CO2 emissions, environmental quality, and climate change impacts.In the context of ecological architecture, the reuse of fly ash, which is produced at a rate of nearly 100 million tonnes annually and occupies approximately 75,000 acres over the past 30 years, is significant. Fly ash can be mixed with cement up to 40%. Recent studies also suggest that recycled plastics or post-industrial waste can serve as excellent insulating materials for flooring and roofing. The use of municipal solid waste and construction and demolition (C&D) debris also holds potential as building materials in the construction sector. This paper aims to provide an understanding of energy-efficient construction and alternative technologies, considering vernacular and cost-effective solutions.

Regarding vernacular materials and energy considerations for roofing options, lime concrete terracing is notably more expensive in both cost and energy consumption. In comparison, alternative roofing options such as flat terracing, mud layer terracing, and mud phuska terracing show significant reductions in cost—63.2%, 62.22%, and 64.78%, respectively. The energy consumption for these alternatives is also lower, at 28.5%, 20.20%, and 23.74%, respectively, compared to lime concrete terracing.

2. Margot Pellegrino, Biswajit et al. conducted a comparison of the estimated costs for facades in Kolkata, India, focusing on walls made of 250mm thick clay bricks, aluminum window shutters with. . The net-zero emissions concrete is sufficiently strong for typical building applications, offering an eco-friendly and dependable alternative to conventional hundred miles power plant in fly ash now Kolkata using fly ash bricks size 190x90x90 and Glazing is now a commonly used material, while timber shutters are increasingly expensive. Currently, aluminum window shutters with glazing are more commonly used in modern buildings. Embodied energy in building materials refers to the amount of energy required to produce and transport materials to the construction site. High embodied energy contributes to greenhouse gas emissions, making it essential to minimize embodied energy for sustainability. International green building standards, such as LEED, do not provide specific guidance for reducing embodied energy, while Indian standards like GRIHA focus on minimizing embodied energy, with criteria set at 16 for fly ash and 15 for other materials. The U.S. government's NIST has developed BEES software to evaluate embodied energy in building materials.Fly ash, a by-product of power plants, is considered to have low embodied energy when used as a building material. Using BEES software, it has been found that the embodied energy of fly ash bricks (according to ASTM C216) is about 0.89 MJ, whereas traditional clay bricks have an embodied energy of 9.3 MJ. For Indian conditions, the embodied energy of clay bricks is estimated at 4.5 MJ, while fly ash bricks require 2.32 MJ. The embodied energy of glass bricks is estimated to be 25.8 MJ/kg.Regarding operational energy demand, the air- conditioned growth rate in India has been increasing by 20- 25% annually in recent years. The domestic sector accounts for 20%, and the private business sector for approximately 25%, with a total growth rate of 100%. The Benefit-Cost Ratio (BCR) represents the total energy saved per Indian Rupee (INR) of investment for each construction option.

4 M. T. S. Lakshmayya, R. Chiranjeevi Rahu et al. (2016) aimed to enhance the quality of construction and promote sustainability by ensuring strength, stability, and durability of the structure using eco-friendly materials. They compared clay bricks with fly ash bricks, showing a 36% reduction in cement usage with fly ash bricks. When using Cellular Lightweight Concrete (CLC), cement reduction was 51.22% compared to clay bricks, and sand usage decreased by 48% compared to clay bricks. In. compared with conventional methods, leading to conclusions. For a G+4 residential building, the costs fly ash bricks at Rs 826.63, and CLC blocks at Rs 1387.33. The costs per cubic meter were Rs 20,677.20 for clay bricks, Rs 11,397.60 for fly ash bricks, and Rs 20,187.80 for CLC blocks. The cubic meter measurement proved to reduction in cement, while sand usage was reduced by 18.75% compared to fly ash bricks ash bricks M. T. S. Lakshmayya, R. Chiranjeevi Rahu et al. (2016) conducted a study on materials required for construction, including clay bricks, fly ash bricks, and lightweight concrete blocks, used in various load-bearing masonry structures. They compared the costs of building materials and labor, considering concrete blocks for the load- bearing foundation and masonry. In 1950, engineering methods for masonry buildings were not widely adopted, with only basic rules of thumb and tables used in codes. When buildings exceeded 3 or 4 stories, RCC (Reinforced Cement Concrete) and steel frames were employed. Recent examples of masonry load-bearing buildings include 12 to 20-story

structures, with wall thicknesses ranging from 25 to 40 cm. One notable example is the Monadnock Building in Chicago, designed by John Rort in 1891, which had an 18 cm thick wall from the base.In India, the strength of construction bricks is typically
between 7 to 10 N/mm², which is considered low for the construction of tall load-bearing masonry buildings. In contrast, in Western countries, medium-quality bricks are stronger, ranging from 30 to 50 N/mm², and are used to construct buildings up to 5 or 6 stories, with brick strength between 17.5 to 25 N/mm². The cost of such structures is often lower than that of RCC buildings.In India, experimental projects conducted by the National Building Organization and the Central Building Research Institute (Roorkee) have studied the use of various eco-friendly materials such as clay bricks, fly ash bricks, and cellular lightweight concrete blocks according to Indian Standard Codes. Literature reviews show that load- bearing masonry construction for mid- to high-rise buildings is becoming more popular. For instance, in Brazil, buildings of up to 15 stories were constructed using masonry walls in 2009 (Santo F.A et al.), showcasing the potential of structural masonry. Similarly, in Switzerland, unreinforced masonry has been tested for buildings up to 18 stories, with a 16-story building constructed using 149.2mm thick load-bearing walls.In the current study, the construction costs for multi-story buildings were evaluated using materials like clay bricks (IS 2212: 1991), fly ash bricks (IS 12894: 2002), and lightweight concrete blocks (IS 2185: 2008, Part IV). The design loads, dead loads, and live loads were calculated using codes like IS 875 (Part I - 1987) and IS 875 (Part II - 1987), with unreinforced masonry guidelines from IS 1905-1987. The methodology included data collection, analysis, and the selection of a construction plan. Structural elements were designed and reviewed, and bricks with suitable compressive strength were chosen based on load calculations. Costs for materials and labor were then estimated and per square meter was as follows : clay bricks at Rs 1486.87 be more cost- effective, depending on the budget, structural strength, and environmental considerations.In conclusion, the study emphasizes the importance of selecting appropriate materials based on cost-effectiveness, structural requirements, and sustainability in the construction industry.

5. 2012 Hossein Zabihi1, Dr. Farah Habib1 et al. In recent years, the main challenge in building construction has been minimizing the social, economic, and environmental impacts of buildings while maintaining their cost-effectiveness and improving quality of life. To address these challenges, sustainable construction has gained importance, as the construction industry plays a key role in sustainable development. Sustainability in buildings is classified into four main categories: environmental, social, economic, and technical issues, with various general factors outlined in each category. Technological advancements are primarily focused on, and architecture has shifted from being "part of the environment" to being "separate from the environment," which has led to environmental degradation and a shift away from economic considerations. Sustainable development aims to provide a better quality of life for all people, both now and in the future. This involves achieving four key objectives globally: 1. promoting social progress that meets the needs of all individuals, 2. ensuring effective environmental protection,) using natural resources wisely, and (4) maintaining stable, high levels of economic growth and employment. The concept of sustainability has evolved to include the principle of the triple bottom line, which emphasizes three pillars: social, environmental, and financial performance.

T. Ramesha, Ravi Prakasha, et al.(2010) In the energy demand throughout the life cycle of buildings, the majority (80-90%) is used for operational energy, which includes energy required for heating, cooling, lighting, and other essential functions. A smaller portion (10-20%) is used for embodied energy, which involves energy consumed during the extraction, processing, manufacturing, transportation of construction materials, and demolition. Energy consumption in residential buildings typically ranges from 150-400 kWh/m³ per year, while office buildings consume around 250-550 kWh/m³ per year. This emphasizes the role of buildings in both social and economic development and highlights the growing need for sustainable growth in the construction industry. Energy's significance in life cycle energy analysis is due to the fact that buildings account for 30-40% of global primary energy usage in residential, office, and commercial sectors. Buildings are also responsible for 40-50% of global greenhouse gas emissions, primarily from fossil fuel-based electricity used for heating, cooling, and other systems. These activities include maintaining internal comfort, water usage, and operating appliances. Lastly, the demolition phase involves destroying the building and transporting debris to landfills or recycling facilities.

Mustafa YÕ lmaza, et al. (2015) The concept of "Sustainability," first defined in the Brundtland Report published in 1989 by the United Nations World Commission on Environment and Development, has become central to numerous studies and practices. The adoption of environmental and energy policies that support economic growth without compromising natural ecosystems has driven governments, organizations, institutions, businesses, non-governmental organizations, and other stakeholders to take action in this regard. Sustainability is based on three interconnected pillars— environmental, economic, and social sustainability—that must function cohesively as a unified system for long-term progress. Environmental sustainability focuses on maintaining ecological balance and ensuring that natural systems are preserved for future generations. It advocates for the use of renewable resources within their regeneration limits, minimizing environmental harm, conserving biodiversity, and safeguarding cultural and historical heritage. Core principles involve reducing pollution, preserving essential life-support systems, and utilizing non-renewable resources wisely. The existing model of economic development is based on unlimited production and consumption, resulting in resource depletion and environmental issues. Economic sustainability, a crucial component of sustainable development, calls for a balance between production and consumption while taking ecological and social factors into account. It focuses on creating new markets, enhancing efficiency to reduce resource and energy consumption, and adding value.

Raja Shahmir Nizam, Cheng Zhang, et al. 2018 This research explores the potential for reducing energy consumption and improving sustainability in building projects by evaluating the energy involved in material production, transportation, and construction. Building Information Modeling (BIM) provides a platform to incorporate sustainability factors, yet its compatibility with Life Cycle Assessment (LCA) tools remains a challenge. Past methods have either partially utilized BIM— requiring data to be exported to external tools, creating gaps— or neglected to maintain LCA outcomes within the BIM framework. To resolve this, the paper introduces a system to directly estimate embodied energy within the BIM environment. A prototype tool was created to calculate energy. associated with materials, transportation, and construction, and its effectiveness was validated through a case study. Buildings are responsible for 40% of global energy consumption and 25% of CO_2 emissions, contributing significantly to environmental concerns such as climate change. While optimizing operational energy has been well-explored, embodied energy—energy consumed during material extraction, transportation, and installation—has received less attention. This paper focuses on the initial embodied energy, which includes energy used for material production and transportation during the initial construction phase.

Jane Anderson and Alice Moncaster 2020 Cement contributes to 7% of global greenhouse gas emissions, primarily due to its use in concrete. This study offers the first comprehensive analysis of Environmental Product Declarations (EPDs) for concrete, focusing on minimizing these environmental impacts. The results are valuable for designers in selecting materials with lower environmental impacts and for manufacturers to compare and reduce their emissions. The research also emphasizes the importance of consistent and transparent reporting of EPDs. It explores the embodied impacts of concrete in buildings and aims to guide policy-makers, designers, and industry leaders by reviewing several hundred verified EPDs for concrete materials. The paper provides a global overview of cement, aggregates, and ready-mix concretes, with follow-up papers addressing industry practices and the influence of boundary decisions on embodied impacts. The paper reviews and analyses published Environmental Product Declarations (EPDs) for cementitious materials, aggregates, admixtures, and ready-mix concrete, highlighting the carbon impacts of these materials. It aims to address the challenges in calculating embodied carbon for concrete, which varies based on mix design and material sources. The study draws from over 500 verified EPDs to provide a comprehensive analysis of carbon impacts, with a focus on standard cement classes, aggregates, and ready-mix concretes. The paper concludes by discussing key inconsistencies in data and offering insights into reducing the embodied carbon of concrete. Methodology examines EPDs for cementitious materials, aggregates, admixtures, and ready-mix concrete, downloaded from various programs and verified according to ISO standards. The focus is on the global warming potential (GWP) from the 'cradle to gate' stages, which include extraction, transport, and manufacturing, while omitting impacts from transport to site, construction, and end-of-life phases. The GWP is measured in CO2 equivalents, referred to as embodied carbon in construction products. The document discusses Environmental Product Declarations (EPDs) for cementitious products, covering 118 products including cements, co-products like fly ash, and products like ground limestone. It evaluates the Global Warming Potential (GWP) of different cement types, with white cements having the highest carbon impact, followed by CEM I, CEM II, and CEM III, with co-products like fly ash having the lowest impact. EPDs from 21 countries were analysed, showing wide variations in the embodied carbon of cement across different regions and product types Key findings include A high correlation between cement impact and clinker content. The importance of secondary fuel use in reducing carbon emissions, though waste fuel impacts are inconsistently reported. Allocation issues for co-products like fly ash, with some EPDs neglecting emissions from the production of these co-products. Ruochen Zeng, et al. This review analyzes research on embodied energy in buildings, focusing on a comprehensive and quantitative assessment based on literature. Key terms, shifts in research focus, emerging trends, significant study areas, and potential future research topics on the embodied energy of buildings are identified through bibliometric analysis. The study, which examines 398 papers, reveals three key interconnected research areas. As low-energy and net-zero energy buildings become more common, the proportion of embodied energy in a building's total life cycle is expected to rise and become increasingly important. Over the past two decades, numerous researchers have explored and published findings on embodied energy in buildings. However, a thorough quantitative review of the literature has been lacking. This study utilizes a bibliometric approach to generate a knowledge map and offer a deeper understanding of the field. Global energy and environmental concerns are recognized as major challenges. According to the World Oil Outlook 2015 report (Ban et al., 2015), it is projected that global energy demand will increase by 49% between 2013 and 2040. The primary objective of this study is to explore the concept of the embodied energy in buildings. According to Koskela (1992), embodied energy refers to the energy expended in the creation of materials used in the construction of a building.

Data Collection: Utilizing the proposed paper retrieval approach,

398 articles were identified after removing duplicates and irrelevant documents. These articles, along with their abstracts, titles, authors, sources, and citation references, were saved as Plain Text files, which formed the basis for further analysis. This research employed bibliometric analysis to enhance the comprehension of studies related to the embodied energy of buildings. The analysis covered 398 papers published over the past two decades, and the findings offered insights into the organization and topics of this area of research.

Robert Dylewski, Janusz Adamezyk 2016 The environmental effects of thermal insulation in buildings, including categories of impact: Approximately 80% of the final energy consumed in the construction industry is used for heating buildings. Given the crucial importance assigned to thermal modernization in European policies, this paper seeks to evaluate the environmental advantages of investing in the thermal insulation of external vertical walls of buildings, using Life Cycle Assessment (LCA) analysis, categorized into three types of impact. Global economic growth is closely tied to energy availability, whether in the form of electricity or thermal energy, which is predominantly produced in Poland using fossil fuels. Although methods for generating renewable energy are widely recognized today, the process of obtaining such energy involves investments that deplete additional natural resources. In Poland's National Action Plan (NAP) for energy efficiency, various initiatives were outlined, including horizontal measures aimed at improving energy efficiency in buildings and public institutions.

Manish K investigate parameter of embodied energy 2017 About half of the global annual energy supply is consumed in the construction, operation, and upkeep of buildings. Since most of this energy is derived from fossil fuels, it significantly contributes to yearly carbon emissions. Operational energy is used for space conditioning, heating, lighting, and powering various building devices. To substantially lower the carbon

footprint of buildings, a comprehensive reduction in both embodied and operational energy is essential. Buildings account for roughly 48% of global energy consumption annually, covering their construction, operation, maintenance, and demolition. Energy is directly used in buildings mainly through delivered energy sources such as electricity and natural gas. Buildings also rely on indirect energy sources through the materials used in construction. Each building material requires primary energy (e.g., coal) and delivered energy (e.g., gasoline) for its production and transportation to the construction site.

Discussion

Several parameters significantly influence the performance of a cement matrix with SCMs. For example, the replacement ratio directly affects porosity and water absorption, with higher replacement levels typically increasing these properties. The water-to-binder (W/b) ratio also plays a crucial role, as a higher ratio leads to increased water absorption. Fineness is another key factor, as finer SCMs can fill voids more effectively, thereby reducing water absorption. Additionally, curing conditions, particularly moist curing, enhance hydration, which reduces porosity and improves matrix density. Chemical composition, especially oxides contributing to pozzolanic activity, further impacts water absorption by refining pore structure. This study results in this part focuses on two primary parameters water-to-binder (W/b) ratio and replacement ratio to evaluate how SCMs behave within the cement matrix. By simplifying the analysis to these variables, it can better understand and compare the effects of SCMs on key properties like porosity, hydration, and water absorption.

The use of recycled aggregates, typically sourced from demolished concrete structures, is an effective way to reduce the consumption of natural resources such as gravel and crushed stone. Traditional concrete production relies on virgin materials, leading to substantial environmental impacts, including quarrying, energy use, and habitat destruction. Recycled aggregates, however, provide a more sustainable alternative by reusing materials that would otherwise contribute to landfill waste.

The future of sustainable concrete production seems promising, especially with the increasing awareness of the environmental impacts of traditional concrete. Technological advancements in material processing, mix design optimization, and quality control are likely to improve the performance and reliability of recycled aggregate concrete. Additionally, the development of new, high-performance SCMs and alternative binding materials, such as geopolymer concrete, holds potential for further reducing the environmental footprint of the construction industry.

Conclusion

This study provides a thorough assessment of 11 Supplementary Cementitious Materials (SCMs), analyzing their effects on the fresh, mechanical, and durability properties of concrete, highlighting the variations in their performance and stressing the importance of choosing the appropriate materials to achieve specific concrete characteristics.

Silica Fume (SF) and **Metakaolin (MK)** improve workability and flow at lower replacement levels; however, higher doses may decrease workability due to increased water demand. **Fly Ash (FA)** enhances workability and extends setting time, especially at lower replacement levels, due to a reduction in heat of hydration. On the other hand, materials like **Ground Granulated Blast Furnace Slag (GGBFS)**, **Rice Husk Ash (RHA)**, **Palm Oil Fuel Ash (POFA)**, **Sugarcane Bagasse Ash (SCBA)**, and zeolite generally lower workability at higher replacement levels. **Eggshell Powder (ESP)** leads to moderate reductions in workability, while **Waste Glass Powder (WGP)** affects fluidity depending on the fineness and quantity of the glass particles used. Many SCMs improve concrete durability by lowering permeability to chloride ions, boosting resistance to sulfate attack, and decreasing water absorption. SF and MK demonstrate significant improvements in resistance to chloride penetration, while GGBFS, FA, and SCBA enhance sulfate resistance and reduce carbonation depth. However, the effects of POFA and ESP on durability vary depending on replacement levels and particle fineness. 4.Microstructural analyses show that finer particles, like those in SF and MK, are particularly effective at filling voids and refining the concrete matrix, enhancing density and reducing porosity. The pozzolanic activity of these materials also promotes the formation of Calcium Silicate Hydrate (C-S–H), improving strength and durability. Materials such as FA and GGBFS, though slower to react, still contribute positively to the microstructure over time. Particle size is crucial, particularly with RHA and WGP, where finer particles are more effective at improving concrete properties.

Declaration of competing interest

The authors state that they have no known conflicting financial interests or personal connections that might have seemed to affect the work presented in this paper.

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