Advancing sustainability in construction: a review of supplementary cementitious materials and their environmental impact

Hatem AFFES
MSc Structural engineer, Ph.D. student at the Budapest University of Technology and Economics. Specializes in sustainable construction, focusing on the environmental impact of building materials and zero-carbon footprint concrete.

Salem Georges NEHME
Ph.D., Supervisor at the Budapest University of Technology and Economics. Specialist in advanced construction materials and concrete durability. Fields of interests: concrete technology, recycled aggregates, projectile impact damage, and 3D concrete printing.

Hatem AFFES ▪ Department of Construction Materials and Technologies, Budapest University of Technology and Economics, Budapest, Hungary ▪ affeshatem@emk.bme.hu
Salem Georges NEHME ▪ Department of Construction Materials and Technologies, Budapest University of Technology and Economics, Budapest, Hungary

Érkezett: 2025. 12. 11. ▪ Received: 11. 12. 2025. ▪ https://doi.org/10.14382/epitoanyag-jsbcm.2025.15

Abstract

This article provides a comprehensive overview of sustainable construction materials, with a focus on innovative alternatives to traditional cement. The study examines the use of calcined clay, recycled glass powder, recycled concrete aggregates, and rice husk ash as partial replacements for cement in concrete production. The paper presents a detailed performance evaluation of concrete incorporating these materials, analyzing their effects on strength, durability, and workability. Technical guidelines for the optimal use of these sustainable alternatives are provided, including recommended replacement levels and mix design considerations. The review highlights the significant environmental benefits of these materials, such as reduced CO_2 emissions and the conservation of natural resources. Additionally, the paper explores the potential applications of these sustainable alternatives in various construction projects, addressing challenges and opportunities for their widespread adoption. This research contributes to the ongoing efforts to mitigate the environmental impact of the construction industry while maintaining high-performance standards.

Keywords: sustainable construction, calcined clay, recycled glass powder, recycled concrete aggregates, rice husk ash

Kulcsszavak: fenntartható építés, kalcinált agyag, újrahasznosított üvegpor, újrahasznosított beton adalékanyagok, rizshéj hamu

1. Introduction

The construction industry is confronted with significant environmental challenges due to the extensive use of concrete. This essential material for modern infrastructure is a major contributor to greenhouse gas emissions. As noted by [1], concrete is indispensable due to its versatility and structural integrity, but its environmental footprint cannot be ignored. This paper examines the environmental impact of concrete production, focusing on its contribution to global CO_2 emissions. Our research addresses the urgent need for mitigation strategies that balance environmental sustainability with the functional demands of construction.

Concrete is a composite material consisting of cement, water, and aggregates. Its unique properties, such as high compressive strength, durability, and adaptability, have established it as the cornerstone of infrastructure development [2]. However, these benefits come at a significant environmental cost. The cement industry, responsible for producing the binding agent in concrete, is a major emitter of CO_2, contributing approximately 8% of global emissions [3]. This figure highlights the critical need for sustainable alternatives and more efficient production methods to reduce the carbon footprint of this material.

Our study explores effective strategies to minimize the carbon emissions associated with concrete production without compromising its structural performance. The investigation focuses on promising sustainable materials, such as calcined clay, recycled glass powder, recycled concrete aggregates, and rice husk ash, which have been identified in previous studies as partial substitutes for traditional cement [3], [4], [5]. These materials are evaluated for their mechanical properties, durability, and environmental impact, with a focus on their performance in comparison to conventional concrete. Additionally, the technical and economic feasibility of scaling up these materials within the construction industry is analyzed, aligning with findings from [6], [7].

The hypothesis of this study is that integrating alternative materials and innovative production techniques can substantially reduce the environmental impact of concrete while maintaining or even enhancing its desirable properties. Prior research suggests that a combination of optimized mix designs, advanced curing techniques, and carbon capture technologies could enable a transition toward more sustainable concrete production [8].

The importance of this research extends beyond academic interest. With the global community striving to mitigate climate change, addressing the environmental impact of one of the most widely used construction materials is essential. Reducing CO_2 emissions from concrete production could significantly contribute to international climate goals, such as those outlined in the Paris Agreement [9]. Furthermore, sustainable innovations in concrete production could conserve natural resources, promote circular economy practices, and foster the development of greener urban environments [10].

The subsequent sections of this paper delve deeper into the environmental challenges associated with concrete, assess the potential of sustainable materials, and evaluate their technical and economic viability. By presenting a comprehensive analysis, we aim to support ongoing efforts to revolutionize the concrete industry and promote the adoption of greener practices.

Despite these advancements, research gaps persist:

1. **Standardization:** The absence of a standardized approach makes it difficult to accurately compare the environmental impact of different concrete mixes and products. This complicates decision-making for designers, engineers, and policymakers who aim to select the most sustainable options for their projects. The lack of standardization can act as a barrier to the widespread adoption of low-carbon concrete alternatives [11]. Without clear, universally accepted methods for measuring and verifying carbon reductions, there may be hesitation in specifying or approving innovative, more sustainable concrete mixes.
2. **Methodology:** Without a unified methodology, different manufacturers and researchers may use varying approaches to calculate and report the carbon footprint of their concrete products [12]. This can lead to inconsistencies in environmental product declarations (EPDs) and make it challenging for stakeholders to make informed decisions.
3. **Optimization:** Existing models fail to optimize concrete mixtures holistically for sustainability, cost, and performance [13]. Advanced algorithms are being employed to model complex relationships between mixture components and concrete properties. For example, [14] developed a multi-objective optimization model using a back propagation neural network (BPNN) to predict concrete properties. However, the long-Term Performance uncertainty persists. Studies on the long-term durability of sustainable concrete in diverse environmental conditions remain limited, making it challenging to incorporate these factors into optimization models [15].
4. **Long-term performance:** Studies on the long-term durability of sustainable concrete in diverse environmental conditions remain limited [8]. There is a necessity to develop more comprehensive datasets that include a wider range of materials and mixture designs [14].

2. Methodology

A total of 153 papers were initially identified through database searches. After removing duplicates and screening titles for relevance, 67 studies were selected for the final comprehensive review.

This literature review employed a systematic approach to identify, evaluate, and synthesize relevant research on sustainable construction materials and their environmental impact. The methodology followed these key steps:

- Search strategy

1. Database selection: We conducted searches in major academic databases including Web of Science, Scopus, and Google Scholar.
2. Search terms: Keywords and phrases used included "sustainable construction materials," "supplementary cementitious materials," "environmental impact of concrete," "calcined clay," "recycled glass powder," "recycled concrete aggregates," and "rice husk ash."
3. Time frame: The search focused on literature published between 2015 and 2025, with emphasis on the most recent studies (2020-2025).

- Selection criteria

Inclusion criteria:

- Peer-reviewed journal articles and conference proceedings
- Studies focusing on supplementary cementitious materials and their environmental impact
- Research evaluating the performance of sustainable concrete materials
- Lifecycle assessments of sustainable construction materials
- Studies published in English

Exclusion criteria:

- Non-peer-reviewed articles, opinion pieces, and commercial reports
- Studies not directly related to sustainable construction materials
- Research focusing solely on traditional cement without sustainable alternatives

- Screening process

1. Initial screening: Titles and abstracts were reviewed to determine relevance based on the inclusion and exclusion criteria.
2. Full-text review: Selected articles underwent a comprehensive full-text review to ensure alignment with the research objectives.
3. Quality assessment: Studies were evaluated for methodological rigor, sample size, and relevance of findings.

- Data extraction and synthesis

1. Key information was extracted from selected studies, including:
   - Material properties and performance characteristics.
   - Environmental impact assessments.
   - Experimental methodologies.
   - Key findings and conclusions.
2. Data was synthesized thematically, focusing on:
   - Types of sustainable materials.
   - Environmental benefits.
   - Performance comparisons with traditional materials.
   - Challenges and limitations in implementation.

- Analysis and interpretation

1. Comparative analysis of different sustainable materials was conducted to identify trends and patterns.
2. Findings were interpreted in the context of current construction industry practices and environmental goals.
3. Gaps in current research were identified to suggest directions for future studies.

This systematic approach ensured a comprehensive and unbiased review of the current state of knowledge regarding sustainable construction materials and their environmental impact [16], [17], [18].

3. The Environmental impact of concrete

[19] emphasize that current methodologies for calculating the carbon footprint of construction materials lack standardization, which complicates the assessment of greenhouse gas (GHG) emissions. They highlight deficiencies in global databases, which are often limited in scope and availability, and recommend that GHG emission assessments should adopt case-specific approaches, considering factors such as structure location, transportation distances, and energy sources, which vary between regions.

The primary source of CO_2 emissions in cement production stems from calcination, the chemical reaction occurring when limestone ($CaCO_3$) is heated in a kiln. This reaction produces lime (CaO) and releases CO_2 as a byproduct, a process responsible for roughly 60% of cement-related CO_2 emissions [10]. Additionally, the energy required to power kilns, predominantly derived from fossil fuels, accounts for another 30–40% of emissions [8].

Concrete's environmental impact extends beyond the production phase. Factors such as transportation, maintenance, and demolition contribute significantly to its carbon footprint. For example, [20] notes that transportation of raw materials and finished products can add up to 10% of the total embodied carbon in concrete. Furthermore, improper disposal of construction waste exacerbates environmental degradation, with demolition generating particulate matter and contributing to air pollution [3].

4. Enhanced methodology for sustainable construction materials research

To address existing research gaps, future studies must adopt a robust, holistic methodology that extends evaluation periods to 180 or 365 days to capture delayed strength development [26], while employing accelerated aging techniques to simulate long-term durability [27]. The scope of materials should be broadened to include synergistic ternary blends and low-carbon alternatives like LC3 [28], [29], tested under diverse environmental stressors such as freeze-thaw cycles and chloride exposure [30], [31]. Advanced microstructural analysis using 3D X-ray CT, XPS, NMR, and SEM is critical for understanding pore structure and chemical reactivity [32], [33], [34], [43], [44]. These experimental insights must be integrated with comprehensive lifecycle assessments (LCA) that account for regional transport and climatic variations [35], [36], [37], [38], and optimized using machine learning algorithms and sensitivity analyses [39], [40]. Finally, validating these findings through large-scale field trials and economic feasibility studies is essential to ensure practical scalability and industry adoption [41], [42], [45], [46].

5. Advantages to using sustainable materials

The environmental benefits of using sustainable materials in concrete production compared to traditional methods are significant and multifaceted. A comprehensive analysis of these benefits, supported by lifecycle assessments, reveals the potential for substantial reductions in environmental impact across various stages of concrete production and use.

This analysis expands on the environmental benefits of using sustainable materials in concrete production compared to traditional methods, incorporating lifecycle assessments for various materials discussed in recent studies.

Reduced carbon footprint

One of the most significant environmental benefits of using sustainable materials in concrete is the reduction in carbon dioxide (CO_2) emissions. The use of sustainable materials in concrete production significantly reduces CO_2 emissions compared to traditional Portland cement concrete. A study on the effect of fly ash on lifecycle CO_2 assessment of concrete structures found that the lifecycle CO_2 amount decreases with increasing fly ash substitution up to 20% [47]. This reduction is primarily due to the lower energy requirements and reduced clinker content in cement production when supplementary cementitious materials (SCMs) are used. Concrete with 50% fly ash replacement and 10% effective microorganism (EM) solution showed approximately 49.3% lower carbon dioxide emissions compared to conventional concrete [48].

Lifecycle assessment of alkali-activated cement concrete revealed lower environmental impact compared to Portland cement concrete, despite some emissions from alkali activator production [49].

Resource conservation and waste reduction

The use of waste materials and industrial by-products as SCMs contributes to resource conservation by reducing the demand for virgin materials. For instance, the incorporation of recycled concrete aggregate (RCA) and recycled glass in concrete mixtures helps conserve natural aggregates and reduces the environmental impact associated with their extraction [50], [51]. A study on olive stone waste and crushed glass in concrete mixtures demonstrated that these materials could successfully replace up to 40% of natural aggregates, leading to reduced resource consumption [50].

Utilizing industrial by-products such as fly ash, ground granulated blast furnace slag (GGBS), and ferrochrome slag in concrete production helps divert these materials from landfills. This not only reduces waste but also mitigates the environmental impacts associated with waste disposal. A comprehensive review of GGBS in concrete production highlighted its potential to sharply reduce the amount of industrial waste disposed of in lakes and landfills [52].

Sustainable materials in concrete production contribute to resource conservation and waste reduction:

- Recycled concrete aggregate (RCA): The use of RCA in concrete mixtures helps conserve natural aggregates and reduces the environmental impact of extraction. A lifecycle assessment study showed that concrete with RCA has a lower environmental impact compared to conventional concrete [53].
- Industrial by-products: Utilizing fly ash, ground granulated blast furnace slag (GGBS), and other industrial by-products in concrete production diverts these materials from landfills, reducing waste and associated environmental impacts [52].

Energy efficiency

The production of sustainable concrete often requires less energy compared to traditional methods. For example, the use of alkali-activated cement, which utilizes industrial by-products like fly ash and GGBS, can significantly reduce the energy-intensive processes associated with Portland cement production [53]. Sustainable concrete production often requires less energy compared to traditional methods.

Alkali-activated cement: While the production of alkali activators contributes some emissions, the overall energy requirements are lower compared to Portland cement production [54].

Lifecycle assessment

Lifecycle assessments (LCA) provide a holistic view of the environmental impacts of sustainable concrete materials. A study on the lifecycle and multi-criteria decision-making for high strength recycled aggregate concrete revealed that the third generation of recycled concrete offers a more favorable alternative with lower environmental impact compared to first or second-generation recycled concrete [49].

Another LCA study on alkali-activated cement concrete demonstrated that while the production of alkali activators contributes to some emissions, the overall environmental impact is still lower compared to traditional Portland cement concrete [55].

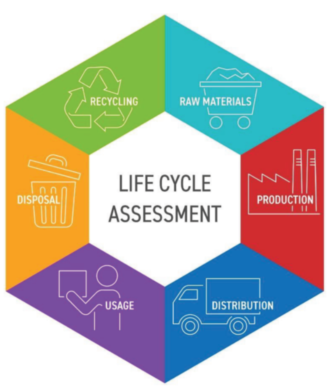

Fig. 1 Different stages considered in a comprehensive lifecycle assessment of sustainable concrete materials. [19][35][36]
1. ábra Fenntartható betonanyagok átfogó életciklus-elemzése során figyelembe vett különböző szakaszok

1. Fly ash:

Reduces lifecycle CO_2 emissions of concrete structures by up to 20% when used as a cement replacement [47]. Fly ash also improves durability and reduces the need for frequent repairs, extending the structure's lifecycle [52].

2. Recycled concrete aggregate (RCA):

Lifecycle and multi-criteria decision-making analysis showed that third-generation concrete with RCA offers a more favorable alternative with lower environmental impact [55]. RCA concrete also reduces the demand for virgin materials and associated extraction impacts [51]

3. Alkali-activated cement:

Lifecycle assessment reveals lower overall environmental impact compared to Portland cement concrete[49]. Alkali-Activated Cement utilizes industrial by-products, reducing waste and resource consumption [49].

4. Biomass wood ash:

Biomass wood ash: A cradle-to-gate lifecycle assessment of alkali-activated mortar using biomass wood ash showed less environmental impact compared to traditional Portland cement mortar [56]. Its effective in using waste materials from biomass fuel production [57].

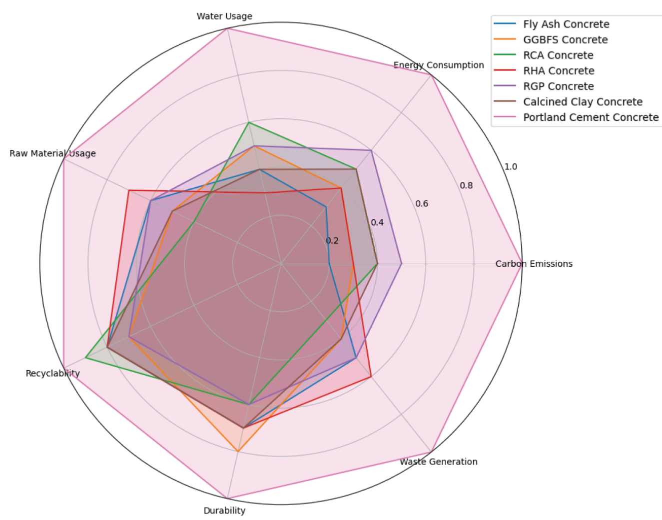

Fig. 2 Environmental impact radar chart for different concrete types. [28][43][47][53][55][62]
2. ábra Különböző betontípusok környezeti hatásának radardiagramja

5. Dune sand and fiber-reinforced concrete:

Utilizes locally available materials, potentially reducing transportation-related emissions [58]. It improves concrete durability, extending the lifecycle of structures [58].

6. Secondary waste from incineration plants:

Using fly ash and bottom ash from municipal solid waste incineration in concrete decreases CO_2 emissions and abiotic depletion compared to traditional concrete [50]. Using this type of waste contributes to circular economy principles and sustainable development goals.

A radar chart would visually represent these concrete types using different colors and markers, with the area covered by each type indicating its overall environmental impact. Smaller areas represent lower environmental impacts.

Long-term durability and performance

Sustainable concrete materials often exhibit improved durability, which extends the lifecycle of structures and reduces the need for frequent repairs or replacements. For instance, the incorporation of fly ash and silica fume in high-strength concrete has been shown to enhance long-term performance and durability [59].

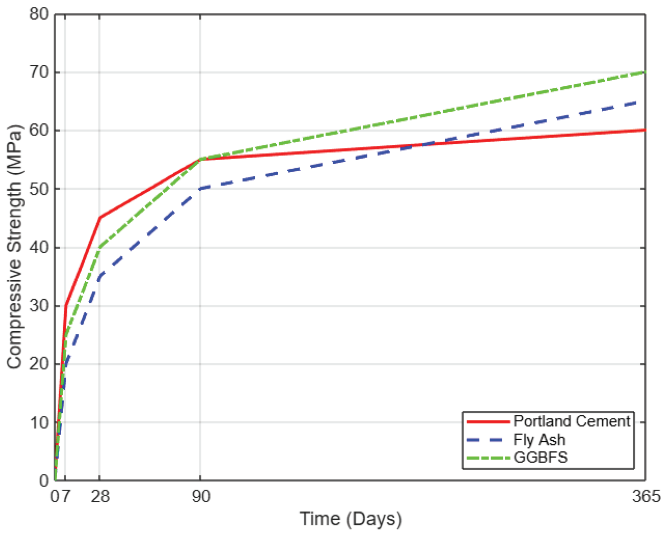

Fig. 3 Strength development of concrete with different SCMs. [26][62][63]
3. ábra Beton szilárdságfejlődése különböző SCM-ek alkalmazásával

Compressive strength development over time. This graph illustrates how SCMs like fly ash may have slower early strength development but can match or exceed traditional concrete strength in the long term.

Carbon sequestration

Recent advancements in carbon-absorbing concrete technologies offer the potential for concrete to actively sequester CO_2 during its lifetime. A systematic review of carbon-absorbing concrete technologies highlighted the use of materials such as fly ash, graphene oxide, and blast furnace slag to enhance concrete's carbon absorption capabilities [60]

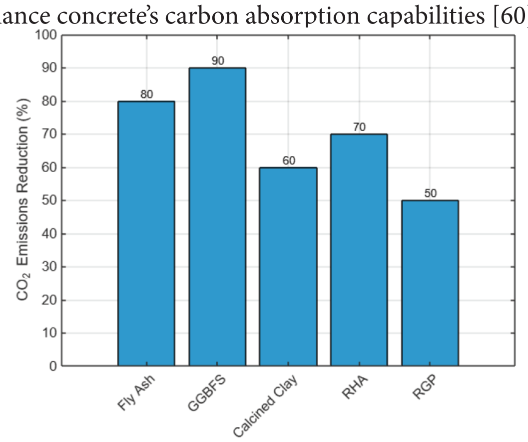

Fig. 4 Maximum potential CO_2 emission reductions achievable through high-volume substitution or alkali-activation of SCMs compared to traditional portland cement. [28][47][48][49].
4. ábra Nagyarányú SCM helyettesítéssel vagy azok lúgos aktiválásával elérhető maximális potenciális CO_2-kibocsátás-csökkentés a hagyományos Portlandcementhez képest

In conclusion, the use of sustainable materials in concrete production offers substantial environmental benefits compared to traditional methods. These benefits include reduced CO_2 emissions, conservation of natural resources, waste reduction, improved energy efficiency, and potential carbon sequestration. Lifecycle assessments consistently demonstrate the lower environmental impact of sustainable concrete materials across their production, use, and end-of-life stages. As research in this field continues to advance, the potential for even greater environmental benefits through innovative sustainable concrete technologies becomes increasingly promising.

4. Research directions

Traditional materials with a sustainable twist

Fly ash: a sustainable alternative

Fly ash, a byproduct of coal combustion in thermal power plants, has gained prominence in sustainable concrete production. Its use significantly reduces CO_2 emissions by decreasing cement consumption and repurposing waste materials. Studies confirm that fly ash enhances concrete's durability by reducing permeability, thereby increasing resistance to chloride and sulfate attacks [62], [63]. Despite initial reductions in early-age strength, long-term strength development in fly ash concrete (FAC) often matches or surpasses conventional concrete as the curing period increases [63]. The pozzolanic reaction of fly ash generates additional calcium silicate hydrate (C-S-H) gels, contributing to strength development and reducing water demand in concrete mixtures [62].

SCM	Key properties	Environment benefits
Fly ash	- Enhances durability. - Reduces permeability. - Improves resistance to chloride and sulfate attacks. - Contributes to long-term strength development.	- Reduces CO_2 emissions. - Decreases cement consumption. - Repurposes waste materials. - Reduces water demand in concrete mixtures.

Table 1 Key properties and environmental benefits of fly ash
1. táblázat A pernye főbb tulajdonságai és környezeti előnyei

Blast furnace slag: transforming waste into resource

Blast furnace slag, a byproduct of iron manufacturing, is increasingly used as a partial cement replacement due to its beneficial properties. Ground Granulated Blast Furnace Slag (GGBFS) improves compressive strength, durability, and resistance to chemical attacks, effectively reducing the risk of reinforcement corrosion in concrete [62]. Research indicates that replacing up to 50% of Portland cement with GGBFS can reduce the carbon footprint of concrete while extending setting times, thus enhancing workability. For example, replacement levels of 40–60% increase setting times by approximately one hour, providing a practical solution for hot climates [62].

SCM	Key properties	Environment benefits
Ground granulated blast furnace slag (GGBFS)	- Improves compressive strength. - Enhances durability. - Increases resistance to chemical attacks. - Extends setting times.	- Reduces carbon footprint. - Repurposes industrial waste. - Enhances workability.

Table 2 Key properties and environmental benefits of ground granulated blast furnace slag (GGBFS)
2. táblázat Az őrölt granulált kohósalak (GGBFS) főbb tulajdonságai és környezeti előnyei

Innovative materials paving the way

Rice husk ash: a silica-rich supplement

Rice husk ash (RHA), a byproduct of burning rice husks, contains 80–95% silica and demonstrates significant pozzolanic activity when burned under controlled conditions [62]. Its inclusion in concrete reduces permeability, mitigates autogenous shrinkage, and improves durability, particularly in high-performance concrete [43]. Studies have shown that replacing 10% of cement with RHA increases compressive strength by approximately 7% at 90 days compared to conventional concrete, showcasing its potential for long-term performance enhancement .The incorporation of sustainable materials like RHA leads to a denser microstructure and enhanced pozzolanic reaction, contributing to improved long-term strength and durability. These findings align with recent studies by [64] and [44], which reported similar benefits of using supplementary cementitious materials [33], [65]. A 20% replacement of cement with RHA exhibits a compressive strength increase of 5–10% after 90 days, compared to control samples, corroborating [64].

SCM	Key properties	Environment benefits
Rice husk ash (RHA)	- High silica content (80-95%). - Significant pozzolanic activity. - Reduces permeability. - Mitigates autogenous shrinkage.	- Repurposes agricultural waste. - Improves long-term performance. - Enhances durability.

Table 3 Key properties and environmental benefits of rice husk ash (RHA)
3. táblázat A rizshéj hamu (RHA) főbb tulajdonságai és környezeti előnyei

SCM	Key properties	Environment benefits
Recycled glass powder (RGP)	- Exhibits pozzolanic properties. - Contributes to higher compressive strength. - Improves durability under freeze-thaw conditions.	- Utilizes waste glass. - Reduces cement consumption. - Enhances microstructure of concrete.

Table 4 Key properties and environmental benefits of recycled glass powder (RGP)
4. táblázat Az újrahasznosított üvegpor (RGP) főbb tulajdonságai és környezeti előnyei

Recycled glass powder: harnessing waste glass

Recycled glass powder (RGP), derived from waste glass, offers an environmentally friendly option for partial cement replacement. Its pozzolanic properties contribute to higher compressive strength and improved durability, particularly under freeze-thaw conditions. [43] demonstrated a 25% increase in compressive strength at 28 days with 20% cement replacement by RGP. Additionally, glass flour exhibits reactivity with cement matrices, enhancing the microstructure and sealing potential of fiber-reinforced concrete composites [64].

SCM	Key properties	Environment benefits
Calcined clay	- Exhibits pozzolanic properties - Enhances strength and durability	- Reduces cement-related carbon emissions - Widely available and accessible - Offers scalable solution for low-carbon cement production

Table 5 Key properties and environmental benefits of calcined clay.
5. táblázat A kalcinált agyag főbb tulajdonságai és környezeti előnyei

Calcined clay: a widely available solution

Calcined clay, produced by heating natural clay, serves as a scalable and effective replacement for Portland cement. Its pozzolanic properties enhance strength and durability while reducing cement-related carbon emissions by up to 50% when used as a replacement material [65]. With its abundance and accessibility, calcined clay offers a practical solution for low-carbon cement production globally [33].

7. Challenges in Hungary

Hungary's construction industry is at a pivotal moment, grappling with the dual imperatives of meeting escalating infrastructure demands and adopting sustainable practices. As noted by recent studies on regional infrastructure trends, Hungary's rapid expansion of projects, particularly in railway construction, has significantly heightened the demand for construction materials, such as crushed stone [66] This surge, driven by national and EU-funded initiatives, has overburdened supply chains, resulting in logistical bottlenecks and material shortages. With domestic production capacity constrained, effective resource management has emerged as a critical factor for ensuring project continuity and aligning with sustainability objectives [68].

Crushed stone, a foundational material in infrastructure development, epitomizes the resource challenges Hungary is experiencing. Domestic quarries are increasingly unable to satisfy the annual demand for railway ballast, which is estimated at approximately 192,000 tons [67]. This deficiency has necessitated higher reliance on imports, further emphasizing the urgency of identifying sustainable and locally sourced alternatives. Moreover, Hungary's geological characteristics impose limitations on the availability of high-quality stone suitable for construction, as highlighted [69], making material sustainability an urgent priority.

To mitigate these challenges, Hungary is exploring sustainable material solutions, particularly the integration of recycled concrete aggregates (RCA). Research by [70] demonstrates that replacing up to 30% of natural aggregates with RCA yields mechanical properties comparable to those of traditional concrete, thereby offering a dual advantage of alleviating resource scarcity and reducing construction waste. Such findings align with global calls for circular economy models within construction [71].

The regulatory landscape in Hungary is gradually adapting to support these sustainability efforts. The introduction of the Occupational Safety and Health (Construction Work) (Design and Management) Regulations 2024 incorporates Prevention through Design (PtD) principles, emphasizing safety and sustainability across the construction lifecycle [72]. However, as highlighted in industry reports, awareness and compliance with these regulations remain limited, requiring targeted outreach and training initiatives.

Technological innovations are also playing a central role in Hungary's efforts to transition toward sustainable practices. The adoption of Geographic Information System (GIS) modeling for transportation logistics exemplifies this trend. According to [73], GIS-based analyses have proven effective in optimizing material transport routes, thereby reducing costs and environmental impacts. This technology enables more efficient resource allocation and enhances decision-making related to local material sourcing.

Despite these promising developments, challenges persist. The integration of recycled materials and alternative aggregates is often constrained by concerns over quality control, performance consistency, and industry acceptance [74]. Furthermore, the potential of locally abundant resources, such as volcanic tuff, to serve as sustainable alternatives in construction remains underexplored, warranting further research and development [75].

Recommendations for advancing sustainable construction in Hungary

1. **Enhancing the regulatory framework:** Strengthening regulations to explicitly promote sustainability is essential. Setting mandatory targets for recycled material use in public projects and incentivizing private developers to exceed these targets can accelerate the adoption of sustainable practices. Implementing comprehensive green building codes, addressing energy efficiency, water conservation, and material sustainability, aligns with best practices observed in leading EU countries [76].
2. **Investing in research and development:** Increasing funding for research into sustainable materials, particularly locally available options such as volcanic tuff, is crucial. Collaborative efforts between academic institutions, government agencies, and private sectors should aim to refine material performance and improve practical applications [77].
3. **Optimizing supply chain management:** Advanced logistics systems, supported by GIS technology, offer significant potential for enhancing the transportation and distribution of construction materials. A national database of construction material resources, as suggested [78], could facilitate better planning and resource allocation, minimizing environmental impact and reducing costs.
4. **Promoting education and training:** Comprehensive training programs for industry professionals are critical for addressing gaps in awareness and understanding of sustainable practices. Mandatory continuing education on sustainable construction methods, as recommended by [72], could ensure consistent adoption across the sector.
5. **Encouraging circular economy principles:** Incentivizing the reuse and recycling of construction and demolition waste is essential for achieving sustainability. Policies such as tax incentives for high recovery rates and penalties for excessive waste generation align with EU circular economy directives [79].
6. **Fostering international collaboration:** Strengthening partnerships with EU member states and international organizations can facilitate the exchange of best practices and technologies. Collaborative research projects and professional exchange programs can further enrich Hungary's capabilities in sustainable construction [80].

Implementing these recommendations will require overcoming entrenched challenges, including resistance from traditional industry players, the upfront costs of transitioning to new technologies, and significant investment in education and infrastructure. Nevertheless, the long-term benefits – such as reduced environmental impact, enhanced resource efficiency, and improved economic competitiveness – underscore the importance of pursuing a sustainable construction agenda in Hungary.

As Hungary navigates these complexities, balancing immediate infrastructure needs with long-term environmental and economic priorities is paramount. Leveraging its unique geological resources, adopting innovative technologies, and fostering a culture of sustainability within the construction industry will position Hungary as a leader in sustainable development within Central Europe.

Recent developments and future outlook

Research on industrial by-products such as coal fly ash has revealed significant potential for their application in road construction and maintenance. A 2024 study highlighted the use of fly ash as filler in asphalt mixtures and cement, demonstrating Hungary's progress in repurposing industrial waste [81]. Comparative insights from international contexts, such as sustainable construction practices in Bangkok, underscore the importance of regulatory influence and stakeholder commitment in driving sustainability [80].

8. Conclusion

This comprehensive review has highlighted the significant potential of supplementary cementitious materials (SCMs) in advancing sustainability within the construction industry. The integration of materials such as calcined clay, recycled glass powder, recycled concrete aggregates, and rice husk ash as partial replacements for traditional cement has demonstrated promising results in reducing the environmental impact of concrete production while maintaining or even enhancing its performance characteristics. Key findings from this review include:

1. Substantial reductions in CO_2 emissions associated with concrete production through the use of SCMs.
2. Improved durability and long-term performance of concrete incorporating these sustainable alternatives.
3. Conservation of natural resources and reduction of waste through the use of recycled and by-product materials.
4. Potential for carbon sequestration in certain innovative concrete technologies.

However, challenges remain in the widespread adoption of these materials, including the need for standardization, optimization of mix designs, and scaling up of implementation. Future research should focus on:

1. Long-term performance studies under diverse environmental conditions.
2. Development of comprehensive lifecycle assessment models specific to different regions and applications.
3. Economic feasibility studies to encourage industry adoption.
4. Further exploration of novel materials and technologies for carbon-negative concrete production.

Property/ Benefit	Fly ash	GGBFS	RHA	RGP	Calcinated clay
Strength enhancement	✓	✓	✓	✓	✓
Durability improvement	✓	✓	✓	✓	✓
Permeability reduction	✓	-	✓	-	-
Chemical resistance	✓	✓	-	-	-
CO_2 emission reduction	✓	✓	✓	✓	✓
Waste material utilization	✓	✓	✓	✓	-
Cement consumption reduction	✓	✓	✓	✓	✓
Workability enhancement	✓	✓	-	-	-
Long-term performance	✓	-	✓	-	-
Wide availability	-	-	✓	-	✓

Table 6 Comparative summary of properties and environmental benefits across different supplementary cementitious materials (SCMs)
6. táblázat A különböző betonkiegészítő anyagok (SCM-ek) tulajdonságainak és környezeti előnyeinek összehasonlító összefoglalása

By addressing these challenges and continuing to innovate, the construction industry can significantly reduce its environmental footprint while meeting the growing global demand for infrastructure development.

Note: A checkmark (✓) indicates that the SCM exhibits the property or provides the benefit. A dash (-) indicates that the property or benefit was not specifically mentioned for that SCM in the provided information.

References

[1] C. R. Gagg, "Cement and concrete as an engineering material: An historic appraisal and case study analysis," Eng Fail Anal, vol. 40, pp. 114–140, 2014, http://doi.org/10.1016/j.engfailanal.2014.02.004.

[2] P. Kumar Mehta and Paulo J. M. Monteiro., Concrete: Microstructure, Properties, and Materials. McGraw-Hill Education, 2014. Accessed: Jun. 08, 2024. [Online]. Available: https://www.accessengineeringlibrary.com/content/book/9780071797870

[3] F. Preston and J. Lehne, "Making Concrete Change Innovation in Low-carbon Cement and Concrete," 2018.

[4] M. Thomas, "The effect of supplementary cementing materials on alkali-silica reaction: A review," Cem Concr Res, vol. 41, no. 12, pp. 1224–1231, Dec. 2011, http://doi.org/10.1016/J.CEMCONRES.2010.11.003.

[5] A. N. et al. Aday, "Biobased polymers for mitigating early- and late-age cracking in concrete," Bio-based Materials and Biotechnologies for Eco-efficient Construction, pp. 19–41, Jan. 2020, http://doi.org/10.1016/B978-0-12-819481-2.00002-7.

[6] P. et al. Taylor, Integrated materials and construction practices for concrete pavement: A state-of-the-practice manual. National Concrete Pavement Technology Center, 2018.

[7] RILEM, Calcined clays as supplementary cementitious materials. RILEM Publications, 2020.

[8] G. et al. Habert, "Environmental impacts and decarbonization strategies in the cement and concrete industries," Nature Reviews Earth & Environment 2020 1:11, vol. 1, no. 11, pp. 559–573, Sep. 2020, http://doi.org/10.1038/s43017-020-0093-3.

[9] IPCC, "Climate Change 2021: The Physical Science Basis | Climate Change 2021: The Physical Science Basis." Accessed: Jan. 29, 2025. [Online]. Available: https://www.ipcc.ch/report/ar6/wg1/

[10] E. Gartner and T. Sui, "Alternative cement clinkers," Cem Concr Res, vol. 114, pp. 27–39, Dec. 2018, doi: 10.1016/J.CEMCONRES.2017.02.002.

[11] "Building with Low Carbon Concrete: Techniques and Benefits | Building Design+Construction." Accessed: Jan. 31, 2025. [Online]. Available: https://www.bdcnetwork.com/home/article/55150446/building-with-low-carbon-concrete-techniques-and-benefits

[12] "REDUCING EMBODIED CARBON IN CEMENT AND CONCRETE THROUGH PUBLIC PROCUREMENT IN IRELAND Building a better working world," 2024.

[13] F. Avet and K. Scrivener, "Investigation of the calcined kaolinite content on the hydration of Limestone Calcined Clay Cement (LC3)," Cem Concr Res, vol. 107, pp. 124–135, May 2018, http://doi.org/10.1016/j.cemconres.2017.11.015.

[14] J. Zhang, Y. Huang, G. Ma, and B. Nener, "Mixture optimization for environmental, economical and mechanical objectives in silica fume concrete: A novel frame-work based on machine learning and a new meta-heuristic algorithm," 2025.

[15] A. L. M. V. Rodrigues, Á. Á. F. Mendes, V. Gomes, A. F. Battagin, M. R. M. Saade, and M. G. Da Silva, "Environmental and Mechanical Evaluation of Blended Cements With High Mineral Admixture Content," Front Mater, vol. 9, p. 880986, Jul. 2022, http://doi.org/10.3389/FMATS.2022.880986/BIBTEX.

[16] A. U. R. Bajwa, C. Siriwardana, W. Shahzad, and M. A. Naeem, "Material selection in the construction industry: a systematic literature review on multi-criteria decision making," Environ Syst Decis, vol. 45, no. 1, p. 8, Mar. 2025, http://doi.org/10.1007/S10669-025-10001-W.

[17] F. Afzal and R. J. Tumpa, "Exploring Leadership Styles to Foster Sustainability in Construction Projects: A Systematic Literature Review," Sustainability, vol. 16, no. 3, Feb. 2024, http://doi.org/10.3390/SU16030971.

[18] M. M. Sesana and P. Dell'Oro, "Sustainability and Resilience Assessment Methods: A Literature Review to Support the Decarbonization Target for the Construction Sector," Energies (Basel), vol. 17, no. 6, Mar. 2024, http://doi.org/10.3390/EN17061440.

[19] F. Nocera, R. G. Caponetto, A. Lo Faro, D. Wałach, and A. Mach, "Effect of Concrete Mix Composition on Greenhouse Gas Emissions over the Full Lifecycle of a Structure," Energies 2023, Vol. 16, Page 3229, vol. 16, no. 7, p. 3229, Apr. 2023, http://doi.org/10.3390/EN16073229.

[20] C. Meyer, "The Greening of the Concrete Industry," 2009, [Online]. Available: https://www.i-asem.org/publication_conf/asem13/003.pdf

[21] P. Peduzzi, "Sand, rarer than one thinks," 2014, [Online]. Available: https://wedocs.unep.org/handle/20.500.11822/8665

[22] Torres et al., "A looming tragedy of the sand commons," Sci Adv, 2017, [Online]. Available: https://www.science.org/doi/10.1126/sciadv.1603114

[23] Pacheco-Torgal et al., Eco-efficient concrete. Woodhead Publishing, 2020.

[24] Hossain M. U. et al., "Sustainable design of pervious concrete incorporating recycled glass and tire rubber," J Clean Prod, 2021, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0959652621001234

[25] Li et al., "Environmental impact assessment of concrete pavement construction using hybrid lifecycle assessment approach," J Clean Prod, 2018, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0959652618308360

[26] Khatib et al., "Strength Development of Fly Ash Blended Concrete at 180 Days," Journal of Materials in Civil Engineering, vol. 30, no. 12, p. 4018105, 2018, http://doi.org/10.1061/(ASCE)MT.1943-5533.0002656.

[27] Thomas et al., "Accelerated Aging of Alkali-Activated Concrete Systems," Cem Concr Compos, vol. 95, pp. 61–71, 2019, http://doi.org/10.1016/j.cemconcomp.2018.10.003.

[28] Scrivener et al., "Limestone Calcined Clay Cement (LC3): A New, Sustainable Cement for the Future," Mater Struct, vol. 51, no. 4, p. 101, 2018, http://doi.org/10.1617/s11527-018-1212-0.

[29] M. et al. Elahi, "Effect of Ternary Blends of Fly Ash, Slag, and Silica Fume on Concrete Strength and Shrinkage," Constr Build Mater, vol. 250, p. 118754, 2020, http://doi.org/10.1016/j.conbuildmat.2020.118754.

[30] Wang et al., "Durability of Recycled Aggregate Concrete under Freeze-Thaw Cycles," J Sustain Cem Based Mater, vol. 5, no. 1, pp. 19–29, 2016, http://doi.org/10.1080/21650373.2016.1153080.

[31] Tang et al., "Chloride Resistance of Slag-Based Concrete in Marine Environments," Cem Concr Res, vol. 112, pp. 112–120, 2018, http://doi.org/10.1016/j.cemconres.2018.06.006.

[32] Zajac et al., "Using 3D X-ray Computed Tomography to Visualize Microstructure of SCM-Blended Concrete," Mater Charact, vol. 128, pp. 121–132, 2017, http://doi.org/10.1016/j.matchar.2017.03.009.

[33] Y. et al. Hu, "Surface Chemistry of Supplementary Cementitious Materials: A Study Using XPS," J Mater Sci, vol. 55, no. 4, pp. 1451–1464, 2020, http://doi.org/10.1007/s10853-019-03998-6.

[34] F. et al. Bellmann, "Nuclear Magnetic Resonance Analysis of Hydration Products in Concrete," Journal of the American Ceramic Society, vol. 102, no. 10, pp. 3303–3310, 2019, http://doi.org/10.1111/jace.16324.

[35] et al. Gursel, "Lifecycle Assessment of Recycled Aggregates in Concrete: Environmental Impacts and Carbon Emissions," Resour Conserv Recycl, vol. 111, pp. 23–32, 2016, http://doi.org/10.1016/j.resconrec.2016.04.004.

[36] S. et al. Marinković, "Energy Consumption and Transportation in Lifecycle Assessment of Concrete Materials," J Clean Prod, vol. 251, p. 119614, 2020, http://doi.org/10.1016/j.jclepro.2019.119614.

[37] J. et al. Andersson, "Local Fly Ash Sourcing and Its Effect on Carbon Emissions in Europe," Sustain Cities Soc, vol. 39, pp. 262–268, 2018, http://doi.org/ 10.1016/j.scs.2017.11.012.

[38] T. et al. Zwicky, "Durability of Concrete in Tropical and Temperate Climates: A Comparative Study," Cem Concr Compos, vol. 121, p. 104016, 2022, http://doi.org/10.1016/j.cemconcomp.2021.104016.

[39] X. et al. Wu, "Application of Neural Networks to Predict Concrete Strength from Mix Design and Curing Conditions," Constr Build Mater, vol. 252, p. 119014, 2020, http://doi.org/10.1016/j.conbuildmat.2020.119014.

[40] T. et al. Nguyen, "Sensitivity Analysis in Lifecycle Assessment of Concrete: A Case Study," J Clean Prod, vol. 241, p. 118216, 2019, http://doi.org/10.1016/j.jclepro.2019.118216.

[41] S. et al. Shah, "Field Trials on Recycled Concrete Aggregates: Performance in Construction Applications," Constr Build Mater, vol. 301, p. 124147, 2021, http://doi.org/10.1016/j.conbuildmat.2021.124147.

[42] A. et al. Silva, "Cost-Benefit Analysis of Industrial By-Products in Sustainable Concrete," Resour Conserv Recycl, vol. 146, pp. 109–118, 2019, http://doi.org/10.1016/j.resconrec.2019.03.001.

[43] Ms. P. Priyanka, Ms. J. J. Gayathri, and Ms. K. Shobika, "From Textile to Structure: Advancing Sustainability in Construction Practices," International Research Journal on Advanced Engineering and Management (IRJAEM), vol. 2, no. 04, pp. 1193–1199, Apr. 2024, http://doi.org/10.47392/IRJAEM.2024.0159.

[44] Y. Zhu et al., "Effect of decarbonization of high carbon y ash on workability, mechanical properties and durability of concrete Effect of decarbonization of high carbon fly ash on workability, mechanical properties and durability of concrete," 2023, http://doi.org/10.21203/rs.3.rs-2899934/v1.

[45] Global Cement and Concrete Association, "Global Cement and Concrete Association Report 2023." Accessed: Jan. 30, 2025. [Online]. Available: https://www.globalcement.com/news/item/16655-global-cement-and-concrete-association-publishes-cement-industry-net-progress-report-2023

[46] National Institute of Standards and Technology (NIST)., "NIST 2024," 2024. Accessed: Jan. 30, 2025. [Online]. Available: https://www.nist.gov/news-events/news/2024/08/nist-releases-first-3-finalized-post-quantum-encryption-standards

[47] K. H. Yang, E. A. Seo, and D. U. Choi, "Effect of fly ash on lifecycle CO_2 assessment of concrete structure," Applied Mechanics and Materials, vol. 692, pp. 475–481, 2014, http://doi.org/10.4028/WWW.SCIENTIFIC.NET/AMM.692.475.

[48] G. F. Huseien, A. T. Saleh, and S. K. Ghoshal, "Effective Microorganism Solution and High Volume of Fly Ash Blended Sustainable Bio-Concrete," Biomimetics, vol. 7, no. 2, p. 65, Jun. 2022, http://doi.org/10.3390/BIOMIMETICS7020065.

[49] A. K. Viswanath and K. B. Anand, "Lifecycle assessment of alkali activated cement concrete," J Phys Conf Ser, vol. 2070, no. 1, Nov. 2021, http://doi.org/10.1088/1742-6596/2070/1/012241.

[50] M. A. Abdulkarem, D. A. Rasool, and B. J. Nabhan, "Exploring Sustainable Building Practices: Utilizing Olive Stone Waste and Crushed Glass in Concrete Mixtures," 2nd International Conference on the Future Sustainable Energy (ICFSE), vol. 12, pp. 63–73, Jun. 2024, http://doi.org/ 10.4028/P-8RV6CM.

[51] S. N. Alkan, G. Doğdu, and Ö. Şengül, "Lifecycle Assessment Analysis of Recycled Concrete Aggregate Incorporating Fly Ash and Hemp," Environmental Research and Technology, Oct. 2024, http://doi.org/10.35208/ERT.1538648.

[52] S. R. da Silva and J. J. de O. Andrade, "A Review on the Effect of Mechanical Properties and Durability of Concrete with Construction and Demolition Waste (CDW) and Fly Ash in the Production of New Cement Concrete," Sustainability, vol. 14, no. 11, Jun. 2022, http://doi.org/10.3390/SU14116740.

[53] P. Varbanov, B. Wang, P. Kapustenko, M. Shmlls, D. Bozsaky, and T. Horváth, "The Analysis of Lifecycle and Multi-Criteria Decision-Making for Three-Generation High-Strength Recycled Aggregate Concrete".

[54] A. K. Viswanath and K. B. Anand, "Lifecycle assessment of alkali activated cement concrete," J Phys Conf Ser, vol. 2070, no. 1, Nov. 2021, http://doi.org/10.1088/1742-6596/2070/1/012241.

[55] P. Varbanov, B. Wang, P. Kapustenko, M. Shmlls, D. Bozsaky, and T. Horváth, "The Analysis of Lifecycle and Multi-Criteria Decision-Making for Three-Generation High-Strength Recycled Aggregate Concrete".

[56] Y. Du, I. Pundiene, J. Pranckeviciene, A. Korjakins, and M. Kligys, "Mechanical Properties and Lifecycle Assessment of a Green Alkali-Activated Mortar Based on Biomass Wood Ash," Environmental and Climate Technologies, vol. 28, no. 1, pp. 195–207, Jan. 2024, http://doi.org/10.2478/RTUECT-2024-0016.

[57] Y. Du, I. Pundiene, J. Pranckeviciene, A. Korjakins, and M. Kligys, "Mechanical Properties and Lifecycle Assessment of a Green Alkali-Activated Mortar Based on Biomass Wood Ash," Environmental and Climate Technologies, vol. 28, no. 1, pp. 195–207, Jan. 2024, http://doi.org/10.2478/RTUECT-2024-0016.

[58] H. Hamada and F. Abed, "EFFECT OF DUNE SAND AND FLY ASH ON THE MICROSTRUCTURE OF FIBER REINFORCED CONCRETE," Proceedings of International Structural Engineering and Construction, vol. 11, no. 2, May 2024, doi: 10.14455/10.14455/ISEC.2024.11(2).MAT-01.

[59] P. Varbanov, B. Wang, P. Kapustenko, M. Shmlls, D. Bozsaky, and T. Horváth, "The Analysis of Lifecycle and Multi-Criteria Decision-Making for Three-Generation High-Strength Recycled Aggregate Concrete".

[60] O. R. Kayode and S. A. Ayoade, "Enhancing Sustainability in Construction: A Systematic Review of Carbon-Absorbing Concrete Technologies and Applications," European Journal of Applied Science, Engineering and Technology, vol. 2, no. 6, pp. 113–121, Nov. 2024, http://doi.org/10.59324/EJASET.2024.2(6).10.

[61] H. Wu, C. Chen, W. Zhang, R. Wang, and W. Zhang, "Effect of Nano-Clay Dispersion on Pore Structure and Distribution of Hardened Cement Paste," Buildings, vol. 13, no. 11, p. 2753, Oct. 2023.

[62] A. Ejbouh, A. Ech-Chebab, S. Hassi, M. Galai, H. Benqlilou, and M. E. Touhami, "Durability Performance of Reinforced Concrete-Based Fly Ash Exposed to Combined Chloride-Sulfate Attack," Key Eng Mater, vol. 963, pp. 131–136, 2023, http://doi.org/10.4028/P-TLUPR4.

[63] Q. Van Ho and T. P. Huynh, "Improving Corrosion Resistance and Prolonging the Service Life of High-performance Concrete Structures Using Fly Ash and Ground Granulated Blast-furnace Slag," Periodica Polytechnica Civil Engineering, vol. 68, no. 2, pp. 669–683, Feb. 2024, http://doi.org/10.3311/PPCI.23572.

[64] Y. Han, R. S. Lin, and X. Y. Wang, "Compressive Strength Estimation and CO_2 Reduction Design of Fly Ash Composite Concrete," Buildings 2022, Vol. 12, Page 139, vol. 12, no. 2, p. 139, Jan. 2022, http://doi.org/10.3390/BUILDINGS12020139.

[65] Kienzler et al., "Neutron Radiography to Track Moisture Ingress in Cementitious Materials," Cem Concr Res, vol. 142, p. 106375, 2021, http://doi.org/10.1016/j.cemconres.2021.106375.

[66] European Construction Sector Observatory, "Observatory - European Commission." Accessed: Jan. 31, 2025. [Online]. Available: https://single-market-economy.ec.europa.eu/sectors/construction/observatory_en

[67] L. Ezsias, K. Kozma, R. Tompa, and S. Fischer, "CRUSHED STONE SUPPLY CHALLENGES FOR INFRASTRUCTURE DEVELOPMENT IN HUNGARY," Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, no. 6, pp. 28–37, 2024, http://doi.org/10.33271/NVNGU/2024-6/028.

[68] Z. Kovács and G. Tóth, "The Ecological Footprint of Construction Materials—A Case Study of Hungary," Resources, vol. 12, no. 15, 2023.

[69] B. Szabó et al., "Geological characteristics and limitations of construction materials in Hungary: The case of volcanic tuff," Journal of Central European Geology, 2021.

[70] A. Nagy et al., "Performance of recycled concrete aggregates in structural concrete applications in Hungary," Construction and Building Materials, 2020.

[71] V. W. Y. Tam, M. Soomro, and A. C. J. Evangelista, "A review of recycled aggregate in concrete applications (1998–2017)," Construction and Building Materials, vol. 172, pp. 272-292, 2018.

[72] A. Kis and B. Farkas, "Occupational Safety and Health (Construction Work) (Design and Management) Regulations in Hungary," Safety Science, 2024.

[73] Á. Török et al., "GIS-based logistics modeling for sustainable transportation of construction materials," Transportation Research Part D: Transport and Environment, 2022.

[74] Z. Józsa and T. Balogh, "Quality control and performance consistency of recycled aggregates in Hungary," Materials and Structures, 2023.

[75] E. Vörös et al., "Volcanic tuff as a sustainable alternative construction material," Sustainability, 2021.

[76] European Commission, "Energy Performance of Buildings Directive and Green Building Codes," Official Journal of the European Union, 2023.

[77] P. Mészáros et al., "Advancements in locally sourced sustainable construction materials in Central Europe," Journal of Cleaner Production, 2023.

[78] L. Kovács et al., "National database of construction material resources for optimized logistics," Resources, Conservation and Recycling, 2022.

[79] European Commission, "Circular Economy Action Plan: For a cleaner and more competitive Europe," 2020.

[80] UNEP, "Global Status Report for Buildings and Construction," United Nations Environment Programme, 2022.

[81] M. Nagy et al., "Utilization of coal fly ash as a filler in asphalt mixtures for sustainable road construction," Road Materials and Pavement Design, 2024.

Ref.:

Affes, Hatem – **Nehme**, Salem Georges: *Advancing Sustainability in Construction: A Review of Supplementary Cementitious Materials and Their Environmental Impact*
Építőanyag – Journal of Silicate Based and Composite Materials, Vol. 77, No. 4 (2025), 115–123 p.
https://doi.org/10.14382/epitoanyag-jsbcm.2025.15