CircularB
Implementation of Circular Economy in the Built Environment

D6 – Report on business models and financial studies (version 2 Feb 2026)

CA21103 – WG2

Diana Bajare
Institute of Materials and Structures, Department of Building Materials and Products, Faculty of Civil Engineering, Riga Technical University, Latvia.

Gabriel Zsembinszki
GREiA Research Group, University of Lleida, Lleida, Spain.

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Introduction

Deliverable 6, titled "Report on Business Models and Financial Studies", is a pivotal output of COST Action CA21103 – CircularB: Implementation of Circular Economy in the Built Environment (https://www.cost.eu/actions/CA21103/). CircularB brings together researchers and practitioners from 39 countries with a common goal: to accelerate the adoption of circular economy principles across all stages of the construction sector. This Action supports knowledge exchange, capacity building, and collaborative research on sustainable transformation of the built environment.

The collaborative nature of CircularB has been instrumental in producing the studies encompassed in this deliverable. The network's activities have fostered unique interdisciplinary and international cooperation, enabling the development of diverse, high-quality research outputs. Each paper included in D6 is a testament to this dynamic research ecosystem, highlighting the value of COST networking in enabling cross-border and cross-sectoral innovation.

The studies presented in this deliverable offer detailed insights into various aspects of circular economy implementation, with a particular focus on material innovation, business model development, financial considerations, market dynamics, and stakeholder engagement. They reflect a shared commitment among COST Action members to generate evidence-based, actionable knowledge that can support the practical realization of a circular economy in construction.

The following sections of this report examine these publications in thematic clusters, presenting their objectives, methodologies, and their specific contributions to the overarching goals of Deliverable 6 and the broader ambitions of CircularB.

Context and Objectives

Deliverable 6 (D6) is a cornerstone output of Work Groupe 2 (WG2) within the broader research initiative dedicated to exploring and accelerating the adoption of circular economy principles in the construction sector. The primary objective of this deliverable is to provide a comprehensive assessment of circular business models and financial frameworks that support sustainable innovation in construction. As the sector transitions from linear to circular processes, a need has emerged to understand how innovations, economic viability, business modelling, stakeholder dynamics, and industrial symbiosis intersect to form a holistic circular economy strategy.

This deliverable consolidates findings from a diverse range of studies published by multiple research teams across Europe. It emphasizes the interconnected nature of material innovation, policy, market mechanisms, financial considerations, and stakeholder engagement, all of which are vital for enabling and sustaining circular construction practices. The contributions included in D6 offer a multidisciplinary, multi-scalar, and empirically grounded understanding of what constitutes effective circularity in the built environment.

Structure of the Deliverable

The report is organized into four key thematic sections:

1. **Innovation in Circular Building Materials and Existing Business Models in Construction**
2. **Market Gaps and Opportunities for Circularity**
3. **Finance for Circularity: Innovations and Challenges**
4. **Stakeholder Roles, Relationships, and Challenges in Implementing Circular Economy Practices**

Each section includes a suite of papers that delve into specific facets of the circular economy, ranging from technical innovations in material reuse to strategic financial assessments and stakeholder-informed frameworks. Together, they construct a panoramic view of the transformation underway in the construction sector.

1. Innovation in Circular Building Materials and Existing Business Models in Construction

A key focus of Deliverable 6 is the identification and analysis of material innovations and their integration into existing business models within the construction industry. This section highlights how specific secondary raw materials (typically treated as waste) can be repurposed to create environmental, economic, and operational value. The selected papers explore how waste-to-resource transitions challenge conventional practices and create the foundation for new circular business models, emphasizing the principles of industrial symbiosis and local valorisation.

The paper **"Turning Agricultural Biomass Ash into a Valuable Resource in the Construction Industry—Exploring the Potential of Industrial Symbiosis" (**https://doi.org/10.3390/buildings15020273**)** proposes a circular business model (CBM) based on industrial symbiosis, where sunflower husk ash (SHA) is added to alkali-activated slag materials created using a hydroxide-containing activator. It investigates the fresh and mechanical properties of mortars, revealing promising results as a tool for promoting the presented CBM. The paper contributes to the circular economy by demonstrating how a waste stream from agricultural energy production can be revalorized within the construction sector. It supports industrial symbiosis – connecting disparate sectors (energy, agriculture, and construction), while also presenting a cost-effective alternative to conventional building materials. Business models based on this synergy foster localized circular loops, reduced material procurement costs, and carbon footprint minimization.

"The Potential of Wood Ash to Be Used as a Supplementary Cementitious Material in Cement Mortars" (https://doi.org/10.3390/buildings15091507) expands on the theme by analysing wood ash from biomass energy production as a potential additive in mortar. Through extensive testing of workability, setting time, and compressive strength, the authors demonstrate how varying proportions of wood ash influence performance outcomes. This study contributes to circular economy theory and practice by validating a closed-loop model in which regional biomass waste is reincorporated into the local construction value chain. It emphasizes decentralized processing and reuse, supporting SMEs and regional economies through low-cost and low-impact innovation.

The paper **"Circular Economy in Practice: A Literature Review and Case Study of Phosphogypsum Use in Cement"** (https://doi.org/10.3390/recycling9040063) offers both a macro- and micro-level analysis of the potential for phosphogypsum (an industrial by-product of fertilizer manufacturing) to be used in cement production. The authors conduct a rigorous literature review and present a case study to contextualize practical challenges and enablers. This paper contributes to circular economy goals by identifying pathways to regulatory alignment, improved public perception, and operational scaling. It highlights the financial, environmental, and legal barriers to waste repurposing, proposing a harmonized European waste classification system to enable market entry. Business models informed by this research must accommodate longer innovation lead times and policy support mechanisms.

In **"A Comprehensive Review on Construction and Demolition Waste Management Practices and Assessment of This Waste Flow for Future Valorization via Energy Recovery and Industrial Symbiosis"** (https://doi.org/10.3390/en17215506), the authors analyse construction and demolition (C&D) waste streams, emphasizing their potential for reuse, recycling, and energy recovery. The study identifies practical barriers to effective C&D waste valorisation and outlines industrial symbiosis models that link waste management with construction material supply chains. The paper supports circular economy advancement by framing C&D waste as a resource reservoir rather than a disposal problem. It advocates for closed-loop construction models where waste from demolition feeds directly into new building projects, supported by digital tracking systems and financial incentives.

The paper **"A Review of Industrial By-Product Utilization and Future Pathways of Circular Economy: Geopolymers as Modern Materials for Sustainable Building"** (https://doi.org/10.3390/su17104536) analyses how the circular economy drives new production models in the construction industry by encouraging the use of industrial waste to manufacture geopolymers as a sustainable alternative to traditional Portland cement. This approach not only significantly reduces greenhouse gas emissions but also promotes the closing of material cycles, aligning with the principles of the circular economy. The valorisation of industrial by-products and their reincorporation into construction processes opens up opportunities for the development of circular business models, where efficient waste management and the production of sustainable materials are integrated as competitive and innovative strategies for a low-carbon economy.

The role of the circular economy as a strategic way to reduce environmental pollution by valorising industrial mineral waste in the production of sustainable construction materials is highlighted in **"The Precursors Used for Developing Geopolymer Composites for Circular Economy - A Review"** (https://doi.org/10.3390/ma17071696). In this context, geopolymers emerge as a promising alternative to Portland cement, enabling the utilization of by-products and reducing environmental impacts. Furthermore, optimizing their composition - considering precursors, activation systems, and additives - opens up opportunities to improve their performance and develop circular business models based on material innovation, resource efficiency, and the reintegration of waste into more sustainable production cycles.

The paper **"The Potential of Wood Construction Waste Circularity"** (https://doi.org/10.3390/environments11110231) investigates end-of-life options for wood waste from construction activities. The authors explore mechanical and thermal processing methods for reuse, emphasizing bio-composite production, insulation panels, and wood-plastic applications. The study contributes to circular economy implementation by evaluating regional logistics, cost-efficiency, and environmental trade-offs. It promotes business models centred on modular disassembly and design for deconstruction, both of which are essential to achieving circular construction at scale.

A digital technology enabler has been developed and advanced to support circular economy actions as reported in **"Digitalisation of Railway Tunnels for Climate Change Adaptation and Enhanced Asset Circularity"** (https://doi.org/10.3390/su16229708). The authors developed a world's first Building Information Modelling (BIM) to enhance asset circularity of an underground built environment. This research integrated six BIM dimensions (2D & 3D models, visualisation, scheduling, cost estimation, and sustainability), involved additional material information with Ansys Granta EduPack v.2021 to measure the expenditure of materials and the carbon footprint, and further applied them to propose adaptation measures for a chosen underground railway. The solution advocates the application of BIM in enhancing asset circularity throughout the whole asset life. The research outcome has revealed the externality and added value of BIM for participatory decision-making mechanisms with relevant KPIs (such as LCA & LCC) that truly benefit all stakeholders and consumers.

The paper **"Eight recommendations to adopt materials passports and accelerate material reuse in construction: insights from academia and practice"** (https://doi.org/10.1038/s44296-025-00079-3) highlights the urgent need to transform the construction industry - one of the most resource-intensive and responsible for nearly 40% of global CO_2 emissions - by adopting material passports as a key tool for advancing towards a circular economy and net-zero emissions. Through eight strategic recommendations, it proposes prioritizing reuse and deconstruction over demolition, developing interoperable material passport frameworks, and fostering databases that track the life cycle of buildings. This approach promotes the traceability and revaluation of resources, facilitating the creation of circular business models based on reuse, material exchange, and collaboration among the various stakeholders in the sector, thus driving a cultural, economic, and environmental transition towards more sustainable construction.

Innovation in circular building materials emphasizes reducing waste, lowering carbon footprints, and integrating recycled resources into construction. The study **"Lightweight, Heat-Insulating, Alkali-Activated Slag Composites with Carbon-Based Biochar Additive and Filler"** (https://doi.org/10.3390/ma19020277) aligns with the principle of environmental sustainability by promoting low-carbon construction materials. It utilizes industrial by-products (slag) and biochar, reducing CO_2 emissions and supporting circular economy objectives. The lightweight and heat-insulating properties contribute to energy efficiency in buildings, further minimizing environmental impact. Biochar waste (BW), derived from waste wood, transforms a biomass by-product into a functional component of construction materials, supporting circular economy goals. The research demonstrates that small BW additions (≈0.25%) enhance compressive strength (44.4 MPa) while larger amounts improve thermal and acoustic insulation, creating multifunctional materials. This dual benefit—mechanical performance and insulation—enables lightweight, energy-efficient building elements, reducing operational energy demand and material consumption.

The aim of the study **"Mechanical Properties of MiniBars™ Basalt Fiber Reinforced Geopolymer Composites"** (https://doi.org/10.3390/ma17010248) was to develop a new MiniBars™ basalt fibre-reinforced geopolymer composite (MiniBars™ FRBC). The fly ash morphology, sizes and structure were determined by optical microscopy and scanning electron microscopy (SEM). New MiniBars™ FRBCs were investigated for structure through optical microscopy and SEM. Also, the flexural strength, the flexural modulus, the tensile strength, the tensile modulus, and the force load at upper yield tensile strength were analysed.

The paper **"The Influence of Alkali-Resistant MiniBars™ on the Mechanical Properties of Geopolymer Composites"** (https://doi.org/10.3390/ma18040778) aimed to fabricate new unidirectional geopolymer composites reinforced with AR MiniBars™ (AR MiniBars™ FRBCs) with advanced mechanical properties and durability. AR MiniBars™ FRBCs were prepared by varying the volume of AR MiniBars™ between 0, 12.5, 25, 50, and 75 vol.% to reinforce the geopolymer paste. The filler used for developing geopolymers was fly ash powder from a coal power plant and was investigated by optical microscopy and scanning electron microscopy (SEM). AR MiniBars™ FRBCs were evaluated for mechanical behaviour, including flexural strength, flexural modulus, tensile strength, tensile modulus, force load at upper yield tensile strength, and compressive strength. Also, the fractured and transversal section of AR MiniBars™ FRBCs specimens were analysed by optical microscopy and scanning electron microscopy (SEM).

The review article **"Review of Geopolymer Nanocomposites: Novel Materials for Sustainable Development"** (https://doi.org/10.3390/ma16093478) presents the current state of knowledge on geopolymers and nanocomposite geopolymers, including their various applications and potential uses. The reader can learn about the latest research in this field and understand the benefits of using nanomaterials in geopolymers. Secondly, this article can help the reader understand the complexity of the processes occurring in geopolymers and nanocomposites, as well as their physicochemical properties. The reader can learn about the factors that influence these properties and the methods used to improve them. Thirdly, this article can help the reader understand the concept of sustainable development in the context of using nanocomposite geopolymers. The reader can learn about the materials used to produce these composites and the benefits of their use, such as waste utilization and reduction of carbon dioxide emissions. Overall, this review article on nanocomposite geopolymers can help the reader understand the latest trends and research results in this field, as well as identify potential applications of these materials.

Taken together, these studies provide a robust foundation for understanding how secondary materials can be integrated into construction processes under new circular frameworks. Each publication contributes practical evidence and conceptual clarity to the broader discussion on business model innovation, demonstrating how waste valorisation can be a core economic driver rather than an externality.

2. Market Gaps and Opportunities for Circularity

This section focuses on identifying barriers and leverage points in the broader adoption of circular economy practices in construction, emphasizing capacity building, market readiness, and stakeholder-driven strategies. These studies uncover how current systems and structures can be adapted to support innovative business models that embrace circularity.

"Challenges of Engineering Skillsets Essential for Driving Circularity of Smart Cities" (https://doi.org/10.3390/app15020809) addresses a critical yet often overlooked element of the circular economy transition: human capital. Through an extensive literature review and stakeholder consultation, the study reveals the misalignment between existing engineering education and the skillsets required for implementing circular solutions in smart cities. These findings point to gaps in systems thinking, interdisciplinary collaboration, and digital literacy. This insight is essential for building business environments that are capable of innovating and responding to the demands of circularity.

"Stakeholder Perspectives on the Costs and Benefits of Circular Construction" (https://doi.org/10.1038/s41598-024-81741-z) contributes valuable empirical evidence on the perceptions of developers, contractors, and regulators regarding the financial and practical implications of circular practices. The paper outlines stakeholder-identified obstacles such as high upfront investment and complex regulatory environments, while also highlighting key benefits including operational savings and sustainability credentials. These findings directly inform business modelling by clarifying real-world priorities and concerns within the construction ecosystem.

The paper **"Management of Household-Generated Construction and Demolition Waste: Circularity Principles and the Attitude of Latvian Residents"** (https://www.mdpi.com/1996-1073/17/1/205) contributes a unique perspective by analysing circularity practices at the household level. The research highlights limited adherence to waste sorting guidelines, constrained by cost, convenience, and low environmental awareness. It emphasizes the role of municipal governments in supporting infrastructure and communication efforts, suggesting targeted interventions to increase compliance and participation. This study illustrates that circularity must be addressed not only in industrial processes but also through local engagement and behavioural change, making it a key consideration in broader market transition strategies.

Together, these studies highlight the interplay between technical innovation, workforce development, consumer behaviour, and stakeholder alignment in enabling market conditions for circular economy integration. They contribute to understanding how policy, education, and industry can co-evolve to remove structural barriers and unlock new circular business opportunities.

3. Finance for Circularity: Innovations and Challenges

This section of Deliverable 6 delves into the financial models, economic considerations, and policy mechanisms necessary to support the widespread implementation of circular economy (CE) practices in the construction sector.

The study **"Stakeholder Perspectives on the Costs and Benefits of Circular Construction"** (https://doi.org/10.1038/s41598-024-81741-z) offers a systematic analysis of how professionals and decision-makers within the construction sector perceive the financial and operational impacts of transitioning to circular methods. Based on extensive survey and interview data collected from multiple European countries, the study reveals a spectrum of views, shaped by roles, responsibilities, and experience levels. Stakeholders identified major perceived benefits of circular construction, such as long-term cost savings, reduced environmental impact, improved building performance, and compliance with evolving regulations. However, the paper also surfaces widespread concerns over initial capital expenditure, fragmented supply chains, and the lack of market demand and familiarity with circular solutions.

Importantly, this paper contributes to the business models and financial studies focus of Deliverable 6 by quantifying these perspectives and linking them to specific construction phases (e.g., design, procurement, demolition). For instance, the study finds that while the demolition and reuse phases are widely seen as cost-saving opportunities, earlier stages like design and certification are often perceived as prohibitively expensive under current models. Such nuanced insights are vital for tailoring circular business models to reflect realistic stakeholder motivations and hesitations, and for crafting targeted incentives or communication strategies.

The chapter is anchored by the forthcoming paper **"Assessing Financial Considerations of Circular Economy Practices Across Life Cycle Stages in the Construction Industry"** by Tleuken et al., which offers a comprehensive examination of financial barriers and enabling conditions throughout the building lifecycle.

The study underscores that although circular economy approaches promise long-term environmental and financial gains, their adoption is frequently hampered by several financial obstacles. These include high initial investment costs, uncertain return on investment, and fragmented or inconsistent regulatory frameworks that fail to incentivize circular practices. By analyzing stakeholder feedback across multiple countries—including Norway, Italy, Sweden, Latvia, and Kazakhstan—the paper identifies where financial barriers are most acute.

Findings reveal that different stages of the construction lifecycle are impacted unequally. While the demolition phase often presents cost-saving opportunities due to material recovery and reuse, earlier stages such as design, planning, and certification are perceived as costly and lacking sufficient financial motivation. This imbalance discourages holistic CE adoption from the project outset.

The paper also presents real-world case studies to illustrate both the successes and challenges of implementing financial support mechanisms for CE. For example, in Norway, strong policy backing has facilitated effective reuse and recycling of construction materials. In contrast, the Swedish case involving Loop Industries highlights the difficulty of maintaining circular innovations at scale without sustained public or private investment.

The study concludes by recommending harmonized regulations, long-term financial incentives, and improved investment strategies to support CE implementation. It emphasizes the need for lifecycle-based cost accounting, public-private partnerships, and innovation-friendly fiscal policies that recognize and reward circular value creation.

These insights collectively support Deliverable 6's goal of examining the financial dimensions of circular business models. They affirm that technical feasibility must be matched by supportive financial infrastructures in order for circular construction to become mainstream and economically sustainable.

4. Stakeholder Roles, Relationships, and Challenges in Implementing Circular Economy Practices

The transition toward a circular economy (CE) in the construction sector necessitates more than just technical innovation or economic feasibility - it critically depends on the engagement, cooperation, and alignment of diverse stakeholders. These include architects, engineers, contractors, investors, government regulators, urban planners, waste managers, and end-users. Understanding how these groups influence and interact with one another, as well as how their interests and perceptions affect decision-making, is vital for designing and implementing effective circular strategies.

Several publications within Deliverable 6 provide in-depth investigations into these socio-institutional aspects, emphasizing the relational dynamics and practical obstacles encountered in real-world CE implementation.

Complementing this, the study **"Comparisons of Stakeholders' Influences, Inter-Relationships, and Obstacles for Circular Economy Implementation on Existing Building Sectors"** (https://doi.org/10.1038/s41598-024-61863-0) employs a social network analysis (SNA) approach to explore how key actors relate to each other in practice. Drawing from a cross-country sample, the paper maps influence networks that reveal which stakeholders hold decision-making power, which serve as mediators or bottlenecks, and where information flow is constrained. The findings show that municipal governments and large construction firms are central actors in advancing or impeding CE practices. Conversely, smaller firms, designers, and end-users often lack access to strategic conversations, despite being crucial for on-the-ground implementation.

This paper directly supports Deliverable 6's emphasis on systemic integration by showing how institutional structures and relationship asymmetries can hinder or enable circularity. It reveals, for example, that the absence of formal cooperation mechanisms between regulatory agencies and private developers frequently leads to inconsistent application of CE principles. Moreover, siloed knowledge and lack of trust among actors emerge as persistent challenges, underscoring the importance of transparent governance, collaborative platforms, and inclusive policy frameworks.

Expanding on this perspective, the paper **"Cultivating Sustainable Construction: Stakeholder Insights Driving Circular Economy Innovation for Inclusive Resource Equity"** (https://www.mdpi.com/2075-5309/14/4/935) contributes further evidence on the significance of stakeholder engagement in enabling circular construction. The study draws from online surveys, structured workshops, and roundtable discussions across multiple countries to investigate how various stakeholder groups perceive circular economy adoption throughout the building life cycle.

The findings emphasize that stakeholder collaboration is critical for translating CE theory into real-world applications. Participants identify key drivers such as transparency, trust, policy support, and inclusive planning mechanisms. The study also introduces the concept of resource equity (ensuring fair access to and distribution of materials and benefits) as a foundational principle for sustainable construction. This work aligns with Deliverable 6's focus on financial studies by illustrating how inclusive strategies can make CE more acceptable, affordable, and feasible across stakeholder types.

By framing stakeholder relationships not only as barriers or facilitators but as co-creators of circular innovation, this paper reinforces the conclusion that effective CE implementation must be collaborative, participatory, and systemic in nature.

Further enriching this discussion, the paper **"Challenges of Engineering Skillsets Essential for Driving Circularity of Smart Cities"** (https://www.mdpi.com/2076-3417/15/2/809) examines the competencies required by engineering professionals to enable CE implementation in urban environments. Drawing from a literature review and interviews with industry experts, the study identifies key hard and soft skills such as systems thinking, sustainability literacy, cross-disciplinary collaboration, and stakeholder communication - that are critical for smart city transitions aligned with CE.

One of the paper's main findings is that current engineering education and professional development pathways often do not equip practitioners with the knowledge or tools necessary for CE integration. As a result, skill gaps in areas like digital modeLling, material flow analysis, and policy comprehension hinder effective participation in CE initiatives. The study calls for restructured curricula and lifelong learning opportunities to build a future-ready workforce capable of addressing circular construction challenges.

In the context of stakeholder roles, the study shows that engineers are not merely technical actors but facilitators of inter-stakeholder coordination, problem solvers across the project lifecycle, and enablers of sustainable innovation. By empowering engineers with the right skills, the paper argues, they can play a transformative role in aligning project outcomes with circular economy goals, particularly in smart cities, where system-wide coordination is essential.

The role of digital technology enablers as strategic instruments to support circular management models and unlock synergic value across value chain stakeholders in the built environment is highlighted in **"Synergic Co-Benefits and Value of Digital Technology Enablers for Circular**

Management Models Across Value Chain Stakeholders in the Built Environment" (https://doi.org/10.3390/civileng6040062). In this context, tools such as Building Information Modelling, digital twins, and extended reality emerge as key facilitators for stakeholder integration, participative decision-making, and cross-functional collaboration throughout the building lifecycle. Furthermore, the co-creation and coordinated implementation of these digital technologies enable the development of viable circular business and management models by overcoming siloed practices, enhancing transparency, and fostering collaborative governance structures essential for implementing circular economy practices in the built environment.

Incorporating this research into Deliverable 6 further emphasizes that achieving a circular built environment depends not only on strategic frameworks and policy instruments but also on equipping professionals with competencies that bridge sectors, scales, and disciplines. Stakeholders must understand and value their roles within the broader transition. Their contributions go beyond diagnostic observations: they offer prescriptive guidance for improving coordination, restructuring incentives, and redesigning governance models to support circular practices. This makes them essential references within Deliverable 6, reinforcing the central thesis that stakeholder engagement and relational dynamics are foundational to sustainable and financially viable business models in the circular built environment.

5. Dissemination of the results

	D6. Report on business models and financial studies, paper collection 15.01.2026	**Countries participated**	**Number of citations in Scopus, 02.02.2026**
1.	**Circular Building Materials and Existing Business Models in Construction**		
1.1.	Turning Agricultural Biomass Ash into a Valuable Resource in the Construction Industry— Exploring the Potential of Industrial Symbiosis DOI: 10.3390/buildings15020273	Serbia, Croatia 2025	4
1.2.	The Potential of Wood Ash to Be Used as a Supplementary Cementitious Material in Cement Mortars DOI: 10.3390/buildings15091507	Latvia, UK 2025	1
1.3.	Circular Economy in Practice: A Literature Review and Case Study of Phosphogypsum Use in Cement DOI: 10.3390/recycling9040063	Latvia, Lithuania 2024	10
1.4.	A Comprehensive Review on Construction and Demolition Waste Management Practices and Assessment of This Waste Flow for Future Valorization via Energy Recovery and Industrial Symbiosis DOI: 10.3390/en17215506	Ukraine, Latvia 2024	24
1.5.	A Review of Industrial By-Product Utilization and Future Pathways of Circular Economy: Geopolymers as Modern Materials for Sustainable Building DOI: 10.3390/su17104536	Poland, Kazakhstan 2025	9

1.6.	The Precursors Used for Developing Geopolymer Composites for Circular Economy—A Review DOI: 10.3390/ma17071696	Romania, Poland 2024	13
1.7.	The Potential of Wood Construction Waste Circularity DOI: 10.3390/environments11110231	Latvia, Lithuania 2024	12
1.8.	Digitalisation of Railway Tunnels for Climate Change Adaptation and Enhanced Asset Circularity DOI: 10.3390/su16229708	UK, Taiwan, Czech Republic, and Luxembourg 2024	2
1.9.	Eight recommendations to adopt materials passports and accelerate material reuse in construction: insights from academia and practice DOI: 10.1038/s44296-025-00079-3	UK 2025	1
1.10.	Lightweight, Heat-Insulating, Alkali-Activated Slag Composites with Carbon-Based Biochar Additive and Filler DOI: 10.3390/ma19020277	Lithuania, Malta 2026	0
1.11.	Mechanical Properties of MiniBars™ Basalt Fiber Reinforced Geopolymer Composites DOI: 10.3390/ma17010248	Romania, Poland, Norway, and Czech Republic 2024	26
1.12.	The Influence of Alkali-Resistant MiniBars™ on the Mechanical Properties of Geopolymer Composites DOI: 10.3390/ma18040778	Romania, Poland, Norway 2025	4
1.13.	Review of Geopolymer Nanocomposites: Novel Materials for Sustainable Development DOI: 10.3390/ma16093478	Romania and Poland 2023	37
2.	**Market Gaps and Opportunities for Circularity**		
2.1.	Challenges of Engineering Skillsets Essential for Driving Circularity of Smart Cities DOI: 10.3390/app15020809	UK, Turkey, Portugal, Latvia, China 2025	1
2.2.	Stakeholder perspectives on the costs and benefits of circular construction DOI: 10.1038/s41598-024-81741-z	Kazakhstan, Portugal, UK, Norway, New Zealand, Latvia, Spain, Albania, Japan 2024	12
2.3.	Management of Household-Generated Construction and Demolition Waste: Circularity Principles and the Attitude of Latvian Residents DOI: 10.3390/en17010205	Latvia 2023	6
3.	**Finance for Circularity: Innovations and Challenges**		
3.1.	Stakeholder perspectives on the costs and benefits of circular construction	Kazakhstan, Portugal, UK, Norway, New Zealand, Latvia, Span, Albania, Japan	12

	DOI: 10.1038/s41598-024-81741-z	2024	
3.2.	Assessing Financial Considerations of Circular Economy Practices Across Life Cycle Stages in the Construction Industry DOI:	Accepted for publication in Circular Economy and Sustainability Authors: Ferhat Karaca, Aidana Tleuken, Ali Turkyilmaz, Thomas Laudal, Ivana Kildsgaard, Giancarlo Paganin	---
4.	**Stakeholders' Roles, Relationships, and Challenges in Implementing Circular Economy Practices**		
4.1.	Comparisons of stakeholders' influences, inter-relationships, and obstacles for circular economy implementation on existing building sectors DOI: 10.1038/s41598-024-61863-0	UK, Germany, Turkey, Latvia 2024	27
4.2.	Cultivating Sustainable Construction: Stakeholder Insights Driving Circular Economy Innovation for Inclusive Resource Equity DOI: 10.3390/buildings14040935	Kazakhstan, Span Portugal 2024	13
4.3.	Challenges of Engineering Skillsets Essential for Driving Circularity of Smart Cities DOI: 10.3390/app15020809	UK, Turkey, Portugal, Latvia, China 2025	1
4.4.	Synergic Co-Benefits and Value of Digital Technology Enablers for Circular Management Models Across Value Chain Stakeholders in the Built Environment DOI: 10.3390/civileng6040062	UK, China, Germany, France, Finland, Czech Republic, Latvia 2025	0

Papers covers

Article

Turning Agricultural Biomass Ash into a Valuable Resource in the Construction Industry—Exploring the Potential of Industrial Symbiosis

Olivera Bedov [1], Ana Andabaka [2] and Suzana Draganić [1,*]

[1] Department of Civil Engineering, Faculty of Technical Sciences, University of Novi Sad, 21000 Novi Sad, Serbia; olivera.bukvic@uns.ac.rs
[2] Faculty of Economics and Business, University of Zagreb, 10000 Zagreb, Croatia; ana.andabaka@efzg.unizg.hr
* Correspondence: suzanav@uns.ac.rs; Tel.: +381-63-173-7390

Abstract: This paper presents a circular business model (CBM) designed to promote the valorization of agricultural biomass ash for producing an alternative binder in construction, aiming to reduce CO_2 emissions and landfill waste. The circular economy framework emphasizes regeneration and restoration to minimize resource and energy use, waste generation, pollution, and other environmental impacts. Aligned with these principles of sustainability, the construction industry, energy sector and food processing industry can establish a shared interest through industrial symbiosis. In the proposed CBM, waste from one industry becomes an input for another. The model leverages industrial symbiosis by using sunflower husk ash (SHA) as an alternative hydroxide activator for alkali-activated materials. A case study of companies in the Republic of Serbia that produce SHA as waste forms the basis for this model, featuring promising results of experimental testing of three alkali-activated mortars produced by activating ground-granulated blast furnace slag (GGBFS) with different SHA contents (15, 25 and 35 wt% GGBFS), instead of commercially available hydroxide activators. The potential of SHA as an alternative activator was assessed by testing flow diameter and compressive strength at 7 and 28 days of curing. The highest 28-day compressive strength was attained for the addition of 25% SHA (28.44 MPa). The promising results provided a valid basis for CBM development. The proposed CBM is stream-based, resulting from merging and upgrading two existing industrial symbioses. This study highlights the benefits of the CBM while addressing the challenges and barriers to its implementation, offering insights into the possible integration of agricultural biomass ash into sustainable construction practices.

Keywords: industrial symbiosis; circular business model; alkali-activated materials; agricultural biomass ash; alternative activator; sunflower husk ash; valorization; sustainability

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1. Introduction

The effort to address the issues of climate change and sustainable development marked the decarbonization of the construction sector as a priority [1]. This resulted in the need for changing the supply and demand paradigm, i.e., transferring from a linear to a circular economy (CE). The CE is an economy model promoting regeneration and restoration concepts to minimize the use of natural resources and energy, waste generation, pollution and other negative impacts on the environment, i.e., to "decouple economic growth and resource use" [2]. The European Commission sees circularity as an essential part of a wider transformation of industry towards climate-neutrality and long-term competitiveness and

buildings

MDPI

Article

The Potential of Wood Ash to Be Used as a Supplementary Cementitious Material in Cement Mortars

Oskars Lescinskis [1], Alise Sapata [2], Girts Bumanis [1], Maris Sinka [2], Xiangming Zhou [3] and Diana Bajare [1,*]

[1] Institute of Sustainable Building Materials and Engineering Systems, Faculty of Civil and Mechanical Engineering, Riga Technical University, 6A Kipsalas, LV-1048 Riga, Latvia; oskars.lescinskis_1@rtu.lv (O.L.); girts.bumanis@rtu.lv (G.B.)

[2] 3D Concrete Printing Laboratory, Institute of Sustainable Building Materials and Engineering Systems, Faculty of Civil and Mechanical Engineering, Riga Technical University, 1P. Valdena, LV-1048 Riga, Latvia; alise.sapata@rtu.lv (A.S.); maris.sinka@rtu.lv (M.S.)

[3] Department of Civil & Environmental Engineering, Brunel University London, Uxbridge, Middlesex, London UB8 3PH, UK; xiangming.zhou@brunel.ac.uk

* Correspondence: diana.bajare@rtu.lv

Abstract: This study explores the application of wood ash (WA) as a partial replacement for PC in mortar. Three pre-treatment methods were applied to WA to enhance its reactivity, and it was then incorporated into mortar at two different substitution levels of 10 and 30%. Tests on compressive and flexural strength were conducted on the hardened mortar samples. All hardened mortar samples containing WA showed a decrease in mechanical properties compared to the reference sample without WA. The highest compressive and flexural strength of the samples with WA were observed for those containing 10% of sieved and slaked WA. The compressive and flexural strength of these samples after 28 days were 56 and 9 MPa, respectively, whereas those of the reference samples were 62 and 10 MPa, respectively. Based on the results, the best-performing samples on the compressive test underwent additional testing for freeze–thaw resistance to assess their durability. The mass loss of the reference sample and that with 10% of sieved and slaked WA after 56 freeze–thaw cycles was 11,800 and 13,800 g/m^2, respectively. The findings revealed that increasing the proportion of WA typically led to a decline in the mechanical properties of mortar compared to conventional mixtures. However, with appropriate pre-treatment techniques, the quality and performance of mortar containing WA were significantly improved, demonstrating its potential as a sustainable alternative in reducing the carbon footprint of PC production.

Keywords: Portland cement; mortar; wood ash; cement replacement

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1. Introduction

Portland cement (PC) is one of the most used materials in the concrete industry [1]. The production of PC is considered highly polluting and emits high amounts of greenhouse gasses. The production of PC alone emits up to 9% of the total anthropogenic CO_2 amount and depletes a huge amount of natural resources [2]. To reduce the global CO_2 emissions, blended cements have been developed, where some clinker is replaced with other materials [3]. Traditionally, coal fly ash, a by-product of coal combustion in thermal power plants, has been widely used as a supplementary cementitious material due to its pozzolanic properties and ability to enhance concrete durability, reduce permeability, and improve workability. However, with the global shift away from coal-fired power generation driven by decarbonization efforts and stricter environmental policies, the availability of coal fly ash has become increasingly constrained. For example, many developed nations, including

recycling

Review

Circular Economy in Practice: A Literature Review and Case Study of Phosphogypsum Use in Cement

Girts Bumanis [1], Danutė Vaičiukynienė [2], Tatjana Tambovceva [3], Liga Puzule [1], Maris Sinka [1], Dalia Nizevičienė [4], Ignacio Villalón Fornés [2] and Diana Bajare [1,*]

[1] Institute of Sustainable Building Materials and Engineering Systems, Faculty of Civil and Mechanical Engineering, Riga Technical University, LV-1658 Riga, Latvia; girts.bumanis@rtu.lv (G.B.); liga.puzule@rtu.lv (L.P.); maris.sinka@rtu.lv (M.S.)

[2] Faculty of Civil Engineering and Architecture, Kaunas University of Technology, Studentu St. 48, LT-51367 Kaunas, Lithuania; danute.vaiciukyniene@ktu.lt (D.V.); ignacio.villalon@ktu.lt (I.V.F.)

[3] Governance and Security Institute, Faculty of Engineering Economics and Management, Riga Technical University, LV-1048 Riga, Latvia; tatjana.tambovceva@rtu.lv

[4] Faculty of Electrical and Electronics Engineering, Kaunas University of Technology, Studentu St. 48, LT-51367 Kaunas, Lithuania; dalia.nizeviciene@ktu.lt

* Correspondence: diana.bajare@rtu.lv

Abstract: The utilization of waste generated from industrial production is a burden to overcome for society to reach a circular economy. Usually, production waste is associated with low-quality materials compared to its natural counterparts. In some cases, high-purity materials are generated, while different hazardous substances such as heavy metals, radioactive elements, or organic chemical substances are pollutants that often limit the materials' further application. One such material that has accumulated for decades is phosphogypsum (PG). The extraction of fertilizers from metamorphous rocks results in large quantities of PG. Until now, PG has been deposited in large stockpiles near the production plant, causing problems for the environment in the surrounding area. However, the chemical composition of PG places it as a high-purity artificial gypsum material, which means that it could be used as a substitution or supplementary material in gypsum-based material production. The concerns, with respect to both legislation and prevailing prejudices in society, about its impurities strongly limit its application. This manuscript reviews current research practices for the effective use of PG and analyzes the importance of the circular economy. A life cycle assessment of current state-of-the-art technologies regarding PG application is proposed.

Keywords: circular economy; byproducts; phosphogypsum; recycling; life cycle assessment

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1. Practice of Circular Economy in the Gypsum Industry

According to the Waste and Resources Action Programme, the circular economy is a concept of transition from the linear "take–make–dispose" model to the optimization of resource utilization by prolonging operational life [1]. The objective is to extract the maximum value from resources through extensive use, fostering a systematic approach that mitigates the adverse environmental effects associated with resource depletion and waste disposal. Circular economy principles are gaining momentum within the communities of practitioners and scholars, exerting influence on extractive industries to transition from a linear economic model to a more circular one. The inherent challenges in the mining sector make this shift particularly demanding. Circular economy approaches in mining primarily emphasize a reduction in natural resource extraction and residual waste, with a notable emphasis on managing waste and byproducts, including mine tailings [2,3]. In contemporary times, policies and business strategies place a strong emphasis on sustainable development, with a particular focus on the principles of the circular economy. This approach extends to addressing the challenges associated with waste and secondary materials,

energies

Review

A Comprehensive Review on Construction and Demolition Waste Management Practices and Assessment of This Waste Flow for Future Valorization via Energy Recovery and Industrial Symbiosis

Natalija Cudecka-Purina [1,2,*], Jekaterina Kuzmina [3], Janis Butkevics [4], Arsirii Olena [5], Oleksii Ivanov [5] and Dzintra Atstaja [4,6,*]

1 Department of Management, BA School of Business and Finance, LV-1013 Riga, Latvia
2 EKA University of Applied Science, LV-1009 Riga, Latvia
3 Department of Economics and Finance, BA School of Business and Finance, LV-1013 Riga, Latvia; jekaterina.kuzmina@ba.lv
4 BA School of Business and Finance, LV-1013 Riga, Latvia; janis.butkevics@ba.lv
5 Department of Information System, Odesa Polytechnic National University, 65044 Odesa, Ukraine; arsiriy@op.edu.ua (A.O.); o.v.ivanov@op.edu.ua (O.I.)
6 Faculty of Social Sciences, Riga Stradiņš University, LV-1007 Riga, Latvia
* Correspondence: natalija.cudecka-purina@ba.lv (N.C.-P.); dzintra.atstaja@ba.lv or dzintra.atstaja@rsu.lv (D.A.)

Abstract: Construction and demolition waste (CDW) is one of the largest contributors to global waste streams, simultaneously posing significant environmental and resource management challenges. The management of CDW, particularly its potential for energy recovery and industrial symbiosis, has garnered increasing attention as part of a circular economy approach. This comprehensive review explores global practices in CDW management, analysing theoretical developments, technological advancements, and emerging resource recovery and reuse trends. Background: CDW accounts for more than a third of all waste generated in the EU. A wide variety of materials, such as concrete, bricks, wood, glass, metals, and plastics, make it a very un-homogenous waste stream with high potential for material recovery through different approaches. Methods: This review draws on an extensive analysis of scientific literature, case studies, and industry reports to assess current practices in the CDW stream and assessment of the feasibility of energy recovery, industrial symbiosis, and object reconstruction. Results: The originality of the current research is based on a Latvian case study on CDW management that provides valuable insights into household-level practices and progress towards relevant UN SDGs. Conclusions: Various CDW streams have an undeniable potential for valorization through various approaches. Currently, the most common approach is recovery and recycling, although CDW has the potential to broaden its application within the circular economy framework. For instance, industrial symbiosis is a solution that can not only boost the valorization of CDW but also significantly increase material circularity.

Keywords: circular economy; construction and demolition waste (CDW); energy recovery; industrial symbiosis; sustainable development

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1. Introduction

The proper management and utilization of CDW arising from the construction, demolition, and maintenance of buildings, infrastructure, and roads play a crucial role in sustainable urban development. This process is essential for several reasons. It significantly reduces the use of landfills and their associated environmental impacts, thereby contributing to environmental protection. Conserving natural resources, such as concrete, bricks, wood, glass, metals, and plastics, aids in conserving natural resources. From an

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Review

A Review of Industrial By-Product Utilization and Future Pathways of Circular Economy: Geopolymers as Modern Materials for Sustainable Building

Kinga Korniejenko [1,*], Janusz Mikuła [1], Karolina Brudny [1], Lyazat Aruova [2], Alibek Zhakanov [2], Assel Jexembayeva [2] and Lailya Zhaksylykova [2]

[1] Faculty of Materials Engineering and Physics, Cracow University of Technology, 31-864 Cracow, Poland; janusz.mikula@pk.edu.pl (J.M.); brudnykarolina@gmail.com (K.B.)
[2] Faculty of Architecture and Civil Engineering, Gumilyov Eurasian National University, Kazhymukan Str. 13, r205, Astana 010008, Kazakhstan; ecoeducation@mail.ru (L.A.); zhakanov888@mail.ru (A.Z.); dzheksembayeva_ae@mail.ru (A.J.); sabyrbayeva_la@enu.kz (L.Z.)
* Correspondence: kinga.korniejenko@pk.edu.pl; Tel.: +48-609974988

Abstract: In the era of increasing climatic requirements and changing approaches towards circular economy (CE), the demand for materials designed with care for the environment is growing. This idea is especially important in the construction industry, where ordinary Portland cement (OPC) production emits a large number of greenhouse gases. The main aim of this article is to demonstrate the possibility of using industrial waste for geopolymer production according to CE goals, including closing material loops. This work is based on a critical analysis of the literature and selected case studies. The most important findings of this article allow us to confirm that the role of industrial waste in the construction industry is growing and that industrial by-products are valuable sources for geopolymer production. The development of sustainable materials allows the introduction of closed loops into production processes by making it possible to reuse materials after the end of use, which is an important issue in the context of introducing CE into practice, especially in existing systems.

Keywords: geopolymers; circular economy; sustainability; recycling; industrial by-products; waste management

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1. Introduction

Geopolymers are amorphous, inorganic, synthetic aluminosilicate polymers created from the synthesis of silicon (Si) and aluminum (Al) and obtained geologically from minerals. Their composition is similar to that of zeolite, however, revealing an amorphous microstructure [1,2]. Geopolymers are most often hard, mechanically resistant, and durable bodies resembling natural stone or concrete [3]. However, they are created by a different mechanism than materials related to cement. The binding of Portland cement is simple: it occurs through the hydration of calcium silicates and the formation of a hydrated C-S-H phase with the released hydroxide levels, along with the bonding of geopolymers and the geopolymer cement, leading them through polycondensation [1]. Geopolymers can be produced based on both natural raw materials and industrial by-products, or even some waste materials [4].

These materials find a lot of application, including in medicine, water purification, and the energy industry, but still, the main area of their use is the construction industry [5,6].

materials

Review

The Precursors Used for Developing Geopolymer Composites for Circular Economy—A Review

Gabriel Furtos [1,*], Doina Prodan [1,*], Codruta Sarosi [1], Dorin Popa [2], Marioara Moldovan [1] and Kinga Korniejenko [3]

1 Raluca Ripan Institute of Research in Chemistry, Babes Bolyai University, 30 Fantanele Street, 400294 Cluj Napoca, Romania; codruta.sarosi@ubbcluj.ro (C.S.); marioara.moldovan@ubbcluj.ro (M.M.)
2 Faculty of Economic Sciences, 1 Decembrie 1918 University of Alba Iulia, 15–17 Unirii Street, 510009 Alba Iulia, Romania; dorinn2005@yahoo.com
3 Faculty of Materials Engineering and Physics, Cracow University of Technology, 31-864 Cracow, Poland; kinga.korniejenko@pk.edu.pl
* Correspondence: gfurtos@yahoo.co.uk (G.F.); doina.prodan@ubbcluj.ro (D.P.)

Abstract: Considering recent climate changes, special importance is given to any attempt to depollute and protect the environment. A circular economy seems to be the ideal solution for the valorization of mineral waste, resulting from various industrial branches, by reintroducing them in the process of obtaining alternative building materials, more friendly to the environment. Geopolymers can be considered as a promising option compared to Portland cement. Information about the influence of the composition of the precursors, the influence of the activation system on the mechanical properties or the setting time could lead to the anticipation of new formulations of geopolymers or to the improvement of some of their properties. Reinforcement components, different polymers and expansion agents can positively or negatively influence the properties of geopolymers in the short or long term.

Keywords: fly ash; geopolymer composites; cement; fibers; circular economy; SEM morphology

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1. Introduction

The exhaustion of natural resources, the degradation of the environment, the large emissions of CO_2 into the atmosphere, and the rising deterioration of the environment have fueled the need for urgent solutions to reduce the negative effects of pollution in order to slow global warming [1]. In this view, the concept of circular economy appeared [2,3], which can provide an option for reusing large amounts of waste, encouraging their reuse in the manufacturing circuit, through innovative methods, to obtain new building materials. Coal represents an important resource for obtaining electricity. However, the coal-burning process produces significant amounts of waste, such as slag and fly ash [2,3]. Improper storage of these wastes can lead to air, soil, or water contamination, leading to a negative impact on the environment. In addition to this waste, there are other examples like glass [4] and bauxite waste [5]. Figure 1 shows the main stages of the circular economy.

The geopolymers introduced by Davidovits [6] are materials based on aluminosilicate precursors with low calcium content and alkaline activation. Davidovits [6] relies on the fact that after the geopolymerization process, a zeolitic material will be obtained, with properties such as hardness, longevity, and thermal stability similar to those of natural rocks. These materials showed good resistance to chemical corrosion, superior mechanical properties, and good durability [7]. On the other hand, the above-described materials are more correctly called alkali-activated materials because they are a combination of cement hydrates and geopolymeric components. The conversion of aluminosilicate precursors can be improved by increasing their reactivity to geopolymerization depending on the type and ratio of the alkaline activators used [8,9].

environments

Article

The Potential of Wood Construction Waste Circularity

Gunita Kiesnere [1], Dzintra Atstaja [1,2,*], Natalija Cudecka-Purina [1] and Rozita Susniene [3]

1 Department of Management, BA School of Business and Finance, LV-1013 Riga, Latvia
2 Faculty of Social Sciences, Rīga Stradiņš University, LV-1007 Riga, Latvia
3 School of Economics and Business, Kaunas University of Technology, 44239 Kaunas, Lithuania
* Correspondence: dzintra.atstaja@ba.lv; Tel.: +371-29-412-245

Abstract: Wood construction waste circularity presents enormous potential to significantly decrease total greenhouse gas (GHG) emissions in the European Union (EU). Latvia could become a frontrunner due to its historic relationship with forestry, wood construction practises and unused potential of the innovative application of wood. This research examines what the potential of "circular wood" in Latvia is, how ready the Latvian wood house construction sector is to engage in a circular economy and wood waste circularity and whether the legal framework is ready to support wood waste management in the country. This study presents a combined approach for systematic wood construction product circularity assessment that includes a review of existing EU and Latvian frameworks for construction and demolition waste (CDW) management and wood construction, a general analysis of wood waste recycling systems and technologies, a quantitative data analysis of construction waste management in Latvia and qualitative data analysis of the Latvian wood house construction sector, and interviews with a focus group of Latvian wood industry representatives. The Latvian scope has allowed us to clarify the pattern methodology and impact points to be replicated, tested and measured further on a broader scale, in other countries, or throughout the whole EU. The main findings reveal a potential life cycle assessment (LCA) verifying the circularity of wood and limitations of wood construction waste circularity in Latvia in terms of wood house construction industry readiness and a legal framework as well as overall social prejudices for circular construction. Findings indicate an overall awareness and level of willingness to participate and engage in the circular construction models among Latvians; however, proactiveness and support (legal and financial) is expected from the government and municipalities. The recommendations point towards improvements in wood waste data management, the wood construction sector and the overall impact on sustainable development goals.

Keywords: circular economy; waste circularity; construction wood; construction waste; wood construction waste; sustainable development

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1. Introduction

The traditional, linear economic development model is based on a take–make–consume–throw away society pattern. This model relies on large quantities of low-cost, accessible materials and energy. Meanwhile, the circular economy is a model of production and consumption which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products, keeping materials in the economic cycle for as long as possible. Thus, the life cycle of products is extended. In practise, it means reducing waste to a possible minimum. When a product reaches the end of its life, its materials are kept within the economy wherever possible thanks to reuse, refurbishment or recycling. Therefore, there are multiple benefits of the circular economy that can be pointed out when it comes to the environment as well as to reducing raw material dependence. Sustainability, circularity and the life cycle of products have become increasingly important to the more sustainable future. The sustainable development and the benefits of circularity can be

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Article

Digitalisation of Railway Tunnels for Climate Change Adaptation and Enhanced Asset Circularity

Sakdirat Kaewunruen [1,*], Yi-Hsuan Lin [2], Harris Rosli [1], Chen-Wei Fan [3], Jan Pesta [4] and François Fohl [5]

[1] School of Engineering, University of Birmingham, Edgbaston B15 2TT, UK; hxr291@alumni.bham.ac.uk
[2] Birmingham Centre for Railway Research and Education, University of Birmingham, Edgbaston B15 2TT, UK; yxl926@student.bham.ac.uk
[3] Taoyuan Metro Corporation, Taoyuan 337601, Taiwan; mikey.fan@tymetro.com.tw
[4] University Centre for Energy Efficient Buildings, Technical University in Prague, Třinecká 1024, 273 43 Buštěhrad, Czech Republic; jan.pesta@cvut.cz
[5] ArcelorMittal, L-4221 Esch-sur-Alzette, Luxembourg; francois.fohl@arcelormittal.com
* Correspondence: s.kaewunruen@bham.ac.uk

Abstract: The climate change adaptation strategies for the railway tunnels project are managed by digital multidisciplinary coordination, or Building Information Modelling (BIM), and the case study is focused on the Taipei Metro (MT) Tamsui–Xinyi Line in Taiwan for the railway tunnel analysis. With increasing climate change impacts (such as flooding, earthquakes, extreme temperature, sea level rise, etc.) on railway infrastructure, BIM offers a transformative approach to enhance resilience. This research integrated six BIM dimensions (2D & 3D models, visualisation, scheduling, cost estimation, and sustainability), involved additional material information with Ansys Granta EduPack v.2021 to measure the expenditure of materials and the carbon footprint, and further applied them to propose adaptation measures for the chosen railway tunnel. This study aims to enhance actions to adapt and mitigate climate change effects on railway tunnels, thereby analysing the negative impact of weather hazards. The climate change adaptation strategies are determined based on the case study, and the integration of expenditure, planning, and greenhouse gas emissions is assessed by implementing BIM. AutoCAD Revit v.2021 and Navisworks 19.4 are the virtual simulation tools for design coordination and scheduling for climate risk assessments. The results demonstrate the feasibility of BIM in managing adaptation projects and enhancing asset circularity at the end of life, showcasing its potential for improving efficiency. This study is the world's first to contribute to enhancing infrastructure management by implementing the advanced capabilities of BIM to develop detailed resilience strategies for railway tunnels.

Keywords: adaptation; BIM; climate change; railway; railway tunnel; resilience; circularity

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1. Introduction

The implementation of Building Information Modelling (BIM) stands as the vital digital representation for overcoming the myriad challenges in infrastructure management within the Architecture, Engineering, and Construction (AEC) industry worldwide [1]. BIM adaptions enhance the comprehensiveness of operation and business aspects due to its high performance in the capability of integrated related information, stakeholder collaboration, and communication, which are inherent difficulties in traditional project management methods. Following BIM's recent extensive growth, it presents benefits for infrastructure in leading sectors like transportation, especially railway projects [2,3]. However, persistent external factors like climate change remain a severe issue that significantly impact the resilience of these railway assets in the future. Garmabaki et al. [4] indicate that the hazards associated with unpredicted climate change result in specific difficulties (train delays, failures, incidents, etc.) for railway infrastructure, operation, and maintenance. Hence, it is imperative to develop sustainable considerations to mitigate the impacts of potential

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Perspective

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Eight recommendations to adopt materials passports and accelerate material reuse in construction: insights from academia and practice

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Ana Rute Costa[1] ✉, Rachel Hoolahan[2] & Rabia Charef[1]

The construction industry is not only one of the most resource-intensive industries, but is also responsible for nearly 40% of global energy-related CO_2 emissions. In this perspective paper we present eight recommendations to adopt materials passports and accelerate material reuse in construction. This approach will enable us to reduce embodied carbon expenditure and address Net Zero Targets. We should: 1) Prioritise the reuse of the whole building; 2) Complete a pre-redevelopment and pre-demolition audit; 3) Prioritise deconstruction over demolition; 4) Prepare a deconstruction plan; 5) Adopt a clear materials passports framework that allows interoperability between platforms and databases; 6) Produce a materials passports database according to the life stage of the building: existing, proposed and completed; 7) Incorporate reused materials in new buildings; 8) Promote regulation that supports a cultural shift to address the economic, social and environmental value of materials. In all of these cases, the involvement of all stakeholders across the industry is crucial to enable material reuse and extend the lifecycle of materials.

The construction industry is one of the most resource-intensive industries, therefore, the construction industry needs to stop compromising the environmental sustainability by optimising resource utilisation, improving construction efficiency, and minimising waste[1]. The construction industry is also responsible for nearly 40% of global energy-related CO_2 emissions[2]. As the energy grid is decarbonising[3] and new buildings have a better energy performance, operational carbon emissions are likely to be lower in the future, in particular for new builds. With a decrease of operational carbon emissions, the embodied carbon in new buildings can represent more than 50% of the total life cycle emissions for new energy-efficient buildings[4]. This is the carbon that is being released into the atmosphere now, by the manufacturers and we can reduce it significantly by reusing existing materials. If global economic development and the construction industry continue focusing on an ever-growing model, building new constructions and demolishing the existing ones, the Net Zero Targets defined by the Paris Agreement[5] will not be fulfilled. The World Green Building Council report defined that by 2030, all new buildings, infrastructure, and renovations should have (at least) 40% less embodied carbon and by 2050 the embodied carbon should be zero[6].

Reducing embodied carbon is a fundamental step towards meeting the Net Zero targets defined worldwide and the construction industry needs to develop a sector specific carbon budget[7]. Embodied carbon emissions in buildings encompass the total carbon footprint associated with the production, transportation, and assembly of building materials[8]. Promoting material reuse is crucial, as it can mitigate these emissions by utilising materials that generally have a lower environmental impact compared to newly manufactured ones. This approach not only addresses the sustainability challenges in the construction industry but also aligns with broader environmental goals[9].

According to Blanco et al. [10] 80% of buildings that will exist in 2050 have been already built, thus it is imperative to retrofit the existing buildings and make the most of the materials already in use. To promote a circular economy, the concept of 3R's (Reduce, Reuse and Recycle) suggested by the European Union (EU) and United Nations (UN) has been widely adopted in many waste regulations across the world[11]. After reducing the need for new buildings and materials, the reuse of existing (buildings and materials) appears to be the most energy-efficient solution for a circular economy by enabling the preservation of material value for a longer period[12]. By accel-

[1]Lancaster School of Architecture, Lancaster University, Lancaster, UK. [2]Orms Designers and Architects Ltd, London EC1V 9BW, UK.
✉e-mail: a.costa@lancaster.ac.uk

materials

Article

Lightweight, Heat-Insulating, Alkali-Activated Slag Composites with Carbon-Based Biochar Additive and Filler

Gintautas Tamošaitis [1], Danutė Vaičiukynienė [1,*], Aras Kantautas [2], Ignacio Villalón Fornés [1], Ruben Paul Borg [3] and Laura Vitola [4]

[1] Faculty of Civil Engineering and Architecture, Kaunas University of Technology, Studentų St. 48, 51367 Kaunas, Lithuania; gintautas.tamosaitis@ktu.lt (G.T.); ignacio.villalon@ktu.lt (I.V.F.)
[2] Faculty of Industrial Engineering and Technology, Lietuvos Inžinerijos Kolegija | Higher Education Institution, Tvirtovės al. 35, 50155 Kaunas, Lithuania; aras.kantautas@lik.tech
[3] Faculty for Built Environment, University of Malta, MSD 2080 Msida, Malta; ruben.p.borg@um.edu.mt
[4] Faculty of Civil and Mechanical Engineering, Riga Technical University, Kipsalas St. 6A, 1048 Riga, Latvia; laura.vitola_1@rtu.lv
* Correspondence: danute.vaiciukyniene@ktu.lt; Tel.: +370-37-300-000

Highlights

What are the main findings?

- Biochar waste (BW) was made from waste wood.
- A small amount of BW (>0.5%) was used as an additive, while a larger amount (1–25%) was used as a filler.
- Samples with 0.25% of BW exhibited the highest compressive strength (44.4 MPa).

What are the implications of the main finding?

- Based on SEM findings, BW had good adhesion with the alkali-activated slag matrix.
- The thermal and acoustic insulation effect of the samples increased with the addition of BW.

Abstract

An alkali-activated slag binder based on biochar was developed in this research. The biochar was produced from waste wood and is referred to as biochar waste (BW). In the alkali-activated slag system, a small amount of biochar (up to 0.5%) was used as an additive, and a larger amount (from 1% to 25%) was used as a filler. The influence of the biochar powder on compressive strength was determined. The hydrated samples were investigated using X-ray diffraction (XRD) analysis and scanning electron microscopy (SEM), and the thermal, acoustical properties, and hydration temperature were also determined. The compressive strength of the alkali-activated slag composite, especially after 7 days, was found to increase slightly due to the introduction of a small amount (0.05–0.5%) of BW powder. The powder in the alkali-activated slag matrix was distributed homogenously, resulting in a reduction in the crack propagation. A larger amount of BW led to a non-homogeneous distribution, and this resulted in a gradual reduction in compressive strength with increasing BW. The highest values of compressive strength at 28 days of hydration (44.4 MPa) were recorded for samples with 0.25% of BW. According to mathematical analysis methods, the compressive strength is mainly influenced by the specific surface area of the initial mix ingredients and the amount of BW additive. In the alkali-activated slag matrix, BW acted as an inert micro-filler, with the dilution effect possibly being the reason for the decrease in the hydration temperature. SEM analysis demonstrated that the BW had a good adhesion with the alkali-activated slag matrix. The thermal and acoustic insulation performance of samples with BW improved. These investigations suggest that BW can be successfully incorporated

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materials

Article

Mechanical Properties of MiniBars™ Basalt Fiber-Reinforced Geopolymer Composites

Gabriel Furtos [1,*], Doina Prodan [1], Codruta Sarosi [1], Marioara Moldovan [1], Kinga Korniejenko [2], Leonard Miller [3], Lukáš Fiala [4] and Nováková Iveta [5]

1 Raluca Ripan Institute of Research in Chemistry, Babes-Bolyai University, 400294 Cluj-Napoca, Romania; doina.prodan@ubbcluj.ro (D.P.); codruta.sarosi@gmail.com (C.S.); mmarioara2004@yahoo.com (M.M.)
2 Faculty of Materials Engineering and Physics, Cracow University of Technology, 31-864 Cracow, Poland; kinga.korniejenko@pk.edu.pl
3 ReforceTech AS, NO-3440 Røyken, Norway; len.miller@reforcetech.com
4 Department of Materials Engineering and Chemistry, Faculty of Civil Engineering, Czech Technical University in Prague, 166 29 Prague, Czech Republic; lukas.fiala@cvut.cz
5 Faculty of Science and Technology, The Arctic University of Norway, N-8505 Narvik, Norway; iveta.novakova@uit.no
* Correspondence: gfurtos@yahoo.co.uk

Abstract: Fly ash-based geopolymers represent a new material, which can be considered an alternative to ordinary Portland cement. MiniBars™ are basalt fiber composites, and they were used to reinforce the geopolymer matrix for the creation of unidirectional MiniBars™ reinforced geopolymer composites (MiniBars™ FRBCs). New materials were obtained by incorporating variable amount of MiniBars™ (0, 12.5, 25, 50, 75 vol.% MiniBars™) in the geopolymer matrix. Geopolymers were prepared by mixing fly ash powder with Na_2SiO_3 and NaOH as alkaline activators. MiniBars™ FRBCs were cured at 70 °C for 48 h and tested for different mechanical properties. Optical microscopy and SEM were employed to investigate the fillers and MiniBars™ FRBC. MiniBars™ FRBC showed increasing mechanical properties by an increased addition of MiniBars™. The mechanical properties of MiniBars™ FRBC increased more than the geopolymer wtihout MiniBars™: the flexural strength > 11.59–25.97 times, the flexural modulus > 3.33–5.92 times, the tensile strength > 3.50–8.03 times, the tensile modulus > 1.12–1.30 times, and the force load at upper yield tensile strength > 4.18–7.27 times. SEM and optical microscopy analyses were performed on the fractured surface and section of MiniBars™ FRBC and confirmed a good geopolymer network around MiniBars™. Based on our results, MiniBars™ FRBC could be a very promising green material for buildings.

Keywords: MiniBars; basalt fiber; fly ash; geopolymer composites; mechanical properties

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1. Introduction

Portland cement is one of the basic components for obtaining concrete, but the main problem is the CO_2 emissions. Despite its high compressive strength and durability, concrete's use is limited by its low tensile strength, crack propagation, and the disadvantage that it has a major role in global warming [1]. The cement industry, as a whole, had a contribution of around 7–8% to CO_2 emissions worldwide [2]. Due to these reasons, alternative methods are constantly being searched for, in order to obtain more ecological materials, able to replace Portland cement totally or partially.

Fly ash, as waste resulting from the burning of coal, also represents a serious problem for the environment. Fly ash could be used in the development of geopolymer concrete as a green building material, a very cheap alternative to Portland cement, that contributes to the circular economy [3–6]. Geopolymer concretes are prepared using the precursors of slag, fly ash, and the activators of NaOH, KOH, etc., and water glass (Na_3SiO_3). At

materials

Article

The Influence of Alkali-Resistant MiniBars™ on the Mechanical Properties of Geopolymer Composites

Gabriel Furtos [1,*], Codruta Sarosi [1], Marioara Moldovan [1], Kinga Korniejenko [2], Michał Łach [2], Viorel Ungureanu [3,4], Leonard Miller [5] and Iveta Nováková [6]

[1] Raluca Ripan Institute of Research in Chemistry, Babes-Bolyai University, 400294 Cluj-Napoca, Romania; codruta.sarosi@gmail.com (C.S.); mmarioara2004@yahoo.com (M.M.)
[2] Faculty of Material Engineering and Physics, Cracow University of Technology, 31-864 Cracow, Poland; kinga.korniejenko@pk.edu.pl (K.K.); michal.lach@pk.edu.pl (M.Ł.)
[3] Department of Steel Structures and Structural Mechanics, Civil Engineering Faculty, Politehnica University Timisoara, 300224 Timisoara, Romania; viorel.ungureanu@upt.ro
[4] Technical Science Academy of Romania, 010413 Bucharest, Romania
[5] ReforceTech AS, 3440 Røyken, Norway; len.miller@reforcetech.com
[6] Faculty of Science and Technology, The Arctic University of Norway, N-8505 Narvik, Norway; iveta.novakova@uit.no
* Correspondence: gfurtos@yahoo.co.uk

Abstract: Geopolymer concrete reinforced with MiniBars™ could be an eco-friendly, innovative, durable, high-strength material substitute for common Portland cement in buildings. AR glass fiber MiniBars™ composites (AR MiniBars™) (ReforceTech AS, Royken, Norway) 60 mm in length were utilized to strengthen the geopolymer matrix for the fabrication of unidirectional geopolymer composites reinforced by AR MiniBars™ (AR MiniBars™ FRBCs). New AR MiniBars™ FRBCs were fabricated by adding different amounts of AR MiniBars™ (0, 12.5, 25, 50, 75 vol.%) into the fly ash geopolymer paste. Geopolymers were obtained by combining fly ash powder with Na_2SiO_3/NaOH in a ratio of 2.5:1, which served as an alkaline activator. AR MiniBars™ FRBCs were cured for 48 h at 70 °C and tested for different mechanical properties. Fly ash, AR MiniBars™, and AR MiniBars™ FRBC were evaluated by optical microscopy and SEM. The addition of AR MiniBars™ increased the mechanical properties of AR MiniBars™ FRBCs. The mechanical properties of AR MiniBars™ FRBCs were heightened compared to the geopolymer without AR MiniBars™; the flexural strength was 18.80–30.71 times greater, the flexural modulus 4.07–5.25 times greater, the tensile strength 3.49–8.27 times greater, the force load at upper yield tensile strength 3.6–7.72 times greater, and the compressive strength for cubic samples 2.75–3.61 times greater. The fractured surfaces and sections of AR MiniBars™ FRBCs were inspected by SEM and optical microscopy analyses, and even though there was no chemical adhesion, we achieved a good micromechanical adhesion of the geopolymer to AR MiniBars™. These results obtained encouraged us to propose AR MiniBars™ FRBCs for application in construction.

Keywords: AR MiniBars; AR glass fiber; fly ash; geopolymer composites; mechanical properties

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1. Introduction

Portland cement is one of the most utilized building materials, but its main problem is global CO_2 emissions [1]. It contributes about 5% to global anthropogenic CO_2 emissions [2]. Portland cement has certain disadvantages, like cracks, shrinkage, a slow setting time, limited resistance to chemical attacks, high energy use, and significant emission of

materials

Review

Review of Geopolymer Nanocomposites: Novel Materials for Sustainable Development

Anna Drabczyk [1], Sonia Kudłacik-Kramarczyk [1,*], Kinga Korniejenko [1], Beata Figiela [1] and Gabriel Furtos [2,*]

[1] Department of Materials Engineering, Faculty of Materials Engineering and Physics, Cracow University of Technology, 37 Jana Pawla II Av., 31-864 Cracow, Poland; anna.drabczyk2@pk.edu.pl (A.D.); kinga.korniejenko@pk.edu.pl (K.K.); beata.figiela@pk.edu.pl (B.F.)

[2] "Raluca Ripan" Institute for Research in Chemistry, Babes-Bolyai University, 30 Fantanele Street, 400294 Cluj-Napoca, Romania

* Correspondence: sonia.kudlacik-kramarczyk@pk.edu.pl (S.K.-K.); gfurtos@yahoo.co.uk (G.F.)

Abstract: The demand for geopolymer materials is constantly growing. This, in turn, translates into an increasing number of studies aimed at developing new approaches to the methodology of geopolymer synthesis. The range of potential applications of geopolymers can be increased by improving the properties of the components. Future directions of studies on geopolymer materials aim at developing geopolymers showing excellent mechanical properties but also demonstrating significant improvement in thermal, magnetic, or sorption characteristics. Additionally, the current efforts focus not only on the materials' properties but also on obtaining them as a result of environment-friendly approaches performed in line with circular economy assumptions. Scientists look for smart and economical solutions such that a small amount of the modifier will translate into a significant improvement in functional properties. Thus, special attention is paid to the application of nanomaterials. This article presents selected nanoparticles incorporated into geopolymer matrices, including carbon nanotubes, graphene, nanosilica, and titanium dioxide. The review was prepared employing scientific databases, with particular attention given to studies on geopolymer nanocomposites. The purpose of this review article is to discuss geopolymer nanocomposites in the context of a sustainable development approach. Importantly, the main focus is on the influence of these nanomaterials on the physicochemical properties of geopolymer nanocomposites. Such a combination of geopolymer technology and nanotechnology seems to be promising in terms of preparation of nanocomposites with a variety of potential uses.

Keywords: geopolymer nanocomposites; sustainable development; inorganic nanoparticles; carbon nanotubes; graphene; nanoclay

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1. Introduction

Geopolymers belong to the group of the fastest-growing polymeric materials. The interest in these inorganic ceramic materials is constantly growing. This is a result of their properties, including acid resistance, porosity, low drying shrinkage, as well as high strength, due to which geopolymers are widely investigated for potential application in the construction industry (e.g., repairing roads, bridges, or other infrastructure) [1–3]. Importantly, geopolymers are also used as a substitute for Portland cement. Compared to Portland cement, geopolymers are cheaper, and their fabrication releases less carbon dioxide [4,5].

The use of geopolymers in wastewater treatment (for removing heavy metals) [6–9], soil stabilization [10], carbon capture and storage [11], or as protective coatings [12,13] is also being investigated. Furthermore, studies on the application potential of these materials for biomedical purposes including tissue engineering [14] or drug delivery systems [15] have also been performed.

applied sciences

Article

Challenges of Engineering Skillsets Essential for Driving Circularity of Smart Cities

Benjamin Neale [1], Sakdirat Kaewunruen [1,*], Dan Li [2], Ayfer Donmez Cavdar [3], Rand Askar [4], Tatjana Tambovceva [5] and Diana Bajare [6]

1 Department of Civil Engineering, University of Birmingham, Birmingham B15 2TT, UK; bxn165@alumni.bham.ac.uk
2 School of Urban Construction and Safety Engineering, Shanghai Institute of Technology, Shanghai 201418, China; danli1992@sit.edu.cn
3 Department of Forest Industry Engineering, Faculty of Forestry, Karadeniz Technical University, 61080 Trabzon, Türkiye; adonmez@ktu.edu.tr
4 Institute for Sustainability and Innovation in Structural Engineering (ISISE), Department of Civil Engineering, University of Minho, 4800-058 Guimaraes, Portugal; rand.askar@hotmail.com
5 Governance and Security Institute, Faculty of Engineering Economics and Management, Riga Technical University, Kalnciema Street 6-506, 1048 Riga, Latvia; tatjana.tambovceva@rtu.lv
6 Institute of Materials and Structures, Faculty of Civil Engineering, Riga Technical University, Kipsalas Street 6A, 1048 Riga, Latvia; diana.bajare@rtu.lv
* Correspondence: s.kaewunruen@bham.ac.uk; Tel.: +44-(0)-121-414-2670

Abstract: This study aims to define specific transferable engineering capabilities needed for the implementation (design and practices) of circular economy (CE) within a smart city setting. We conducted a critical literature review of over 100 studies on the core values of CE and smart cities to investigate the knowledge gap in this topic and understand what specific skillset is employed by industry experts that can be harnessed on a wider scale, which can allow for the optimization of CE. There is a lack of research on the skillsets needed to implement a circular economy in any setting, and there are very few studies on circularity practices in a smart city setting. Primary data collection allows us to bridge this knowledge gap, yielding new findings that do not already exist concerning the skillset employed by experts in the field, which can positively impact the smart city settings in which a circular economy is implemented. We conducted a qualitative analysis based on expert interviews of 21 participants who have experience in the circular economy. This information will benefit the industry by informing businesses and councils about the key skillsets and capabilities to look out for when employing people to implement any aspect of circular practices in a smart city setting, with an emphasis on enhancing efficiency, achieving deliverables, and thinking systemically to address complex challenges they may face during the implementation. We also investigated the implementation of CE in smart cities to provide a well-rounded view of the different achievements and challenges faced during the process. This mainly focuses on the work of governance in smart circular cities, a factor that has many important implications and externalities in different sectors. This study describes the methodology adopted to formulate a detailed questionnaire for expert interviews with respect to the skill gap and capabilities necessary for working in the industry, the results of which aid discussions regarding the different challenges faced in CE implementation. Our findings reveal that background knowledge in engineering and sustainability is the most 'highly critical' hard skill according to the experts, while communication and stakeholder engagement are the essential soft skills required to ensure the success of a circular economy within smart city settings.

Keywords: engineering education; technical competency; skillset; transferable capability; circular economy; smart city; built environment; expert interviews; grounded theory

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Stakeholder perspectives on the costs and benefits of circular construction

Ferhat Karaca[1✉], Aidana Tleuken[1,13], Hamad Hassan Awan[1], Rand Askar[2], Mustafa Selçuk Çıdık[3], Anel Iskakova[1], Ali Turkyilmaz[4], Thomas Laudal[4], Serdar Durdyev[5], Huseyin Atakan Varol[6], Adriana Salles[2], Diāna Bajāre[7], Tatjana Tambovceva[8], Gabriel Zsembinszki[9], Genesis Camila Cervantes Puma[2], Zhanna Kapsalyamova[10], Dorina Kripa[11], Dina Azhgaliyeva[12], Xhesila Nano[11], Luisa F. Cabeza[9] & Luís Bragança[2]

The construction industry significantly impacts the environment through natural resource depletion and energy consumption, leading to environmental degradation. Circular Economy (CE) material efficiency strategies—such as material reuse, design for disassembly, prefabrication, and recycling—offer promising solutions for reducing resource consumption and waste. This paper explores stakeholders' perspectives on the costs and benefits of implementing CE material efficiency strategies in the construction industry, using the 3-R (Reduce, Reuse, Recycle) framework. By analyzing data from 382 participants, it assesses perceptions of costs and benefits, uncovering regional differences. The findings highlight that studied European stakeholders prioritize reuse and design for disassembly, while studied non-European countries focus on offsite production and material reuse optimization. Despite these differences, both groups view waste reduction as a key benefit, due to the cost savings it provides. By highlighting regional drivers and barriers to CE adoption, this research establishes a foundation for developing targeted policies and collaborative strategies to advance CE implementation in construction worldwide.

Keywords Construction industry, Circular economy, Recycling, Waste management, Reuse, Machine learning

The construction industry, heavily reliant on natural resources and characterized by high energy consumption, contributes significantly to environmental issues such as elevated greenhouse gas (GHG) emissions, air pollution, environmental degradation, and global warming. Specifically, building construction alone accounts for 10% of global GHG emissions and 6% of global energy consumption[1]. Reducing emissions within the construction sector is crucial to meet global net-zero emission targets. Recognizing this, adopting CE principles—aligned with Industry 4.0 objectives—holds significant promise for reducing GHG emissions across the construction supply chain.

Circular Economy (CE) is a systemic approach aimed at decoupling economic development and activity from the consumption of finite resources[2]. In response to the inefficiencies of the current linear economic model, CE strives to establish a closed-loop system within the value chain, maximizing resource use and minimizing waste generation[3]. Notably, approximately 80% of construction materials end up as waste at the

[1]Department of Civil and Environmental Engineering, School of Engineering and Digital Sciences, Nazarbayev University, Astana, Kazakhstan. [2]Department of Civil Engineering, ISISE, ARISE, University of Minho, Guimarães, Portugal. [3]The Bartlett School of Sustainable Construction, University College London, London, UK. [4]Department of Innovation Management and Marketing, UiS School of Business and Law, University of Stavanger, Stavanger, Norway. [5]Department of Engineering and Architectural Studies, Ara Institute of Canterbury, Christchurch, New Zealand. [6]Institute of Smart Systems and Artificial Intelligence (ISSAI), Nazarbayev University, Astana, Kazakhstan. [7]Institute of Sustainable Building Material and Engineering Systems, Faculty of Civil Engineering and Mechanical Engineering, Riga Technical University, Riga, Latvia. [8]Governance and Security Institute, Faculty of Engineering Economics and Management, Riga Technical University, Kalnciema Str. 6-506, Riga, Latvia. [9]GREiA Research Group, University of Lleida, 25001 Lleida, Spain. [10]Department of Economics, School of Sciences and Humanities, Nazarbayev University, Astana, Kazakhstan. [11]University of Tirana, Tirana, Albania. [12]Asian Development Bank Institute (ADBI), Tokyo, Japan. [13]Department Industrial Engineering and Business Information Systems, University of Twente, Enschede, The Netherlands. ✉email: Ferhat.karaca@nu.edu.kz

energies

Article

Management of Household-Generated Construction and Demolition Waste: Circularity Principles and the Attitude of Latvian Residents

Inese Mavlutova [1,*], Dzintra Atstaja [2,*], Sandra Gusta [3] and Janis Hermanis [1]

[1] Department of Economics and Finance, BA School of Business and Finance, LV-1013 Riga, Latvia; janis.hermanis@ba.lv
[2] Legal Department, Faculty of Law, Riga Stradins University, LV-1007 Riga, Latvia
[3] Faculty of Forest and Environmental Sciences, Latvia University of Life Sciences and Technologies, LV-3001 Jelgava, Latvia; sandra.gusta@lbtu.lv
* Correspondence: inese.mavlutova@ba.lv (I.M.); dzintra.atstaja@rsu.lv (D.A.); Tel.: +371-29412245 (D.A.)

Abstract: This study aims to investigate to what extent the construction and demolition waste generated by households is managed by the principles of circularity and to identify the main influencing factors in the behavior of households regarding the circularity-based management of construction waste in Latvia. The current research presents principles of circularity of household-generated waste based on a systematic literature review, and the data obtained from a survey were analyzed using both descriptive and inferential statistics. This study clarifies the circular economy rationale for construction and demolition waste (CDW) management in Latvia and proposes further development to promote the achievement of sustainable development goals and increased energy efficiency. The results reveal that the observance of circular economy principles in construction and demolition waste management among Latvian households does not correspond to good circular economy practices due to attitudes toward environmental issues, expenses, and logistics; thus, compliance with these principles and legislation as well as closer cooperation between municipalities and households can promote significant economic benefits.

Keywords: construction and demolition waste; waste management; households; circularity; energy; awareness; expenses

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1. Introduction

Recent studies emphasize the development of circularity and its importance in sustainability, which has a positive effect on increasing the efficiency of building materials and energy use and reducing the impact of emissions [1,2]. Reasonable construction and demolition waste management and the use of environmentally friendly materials as well as the introduction of circularity principles, with special emphasis on digital solutions, have a clear positive effect on the reduction in primary resource consumption [3–6].

Construction and demolition waste constitutes a large part of the total mass of waste, has a relatively low environmental impact, and is inert but characterized by a high volume and weight. The construction sector is responsible for over 35% of the EU's total waste generation; consequently, the large environmental impact of CDW is an important logistical and land-use issue [7]. Thus, CDW management is a priority for most environmental programs worldwide, especially in Europe [8].

In recent years, the EU has activated certain measurements, guidelines, and directives to move toward greater support for a sustainable and circular economy; in 2020, the EU Commission developed a circular economy action plan aimed to promote more sustainable product design, reduce the amount of waste, and support opportunities for consumers to use repaired goods, including in the construction sector [9]. In 2021, the EU Parliament

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Comparisons of stakeholders' influences, inter-relationships, and obstacles for circular economy implementation on existing building sectors

Sakdirat Kaewunruen[1]✉, Patrick Teuffel[2], Ayfer Donmez Cavdar[3], Otso Valta[4], Tatjana Tambovceva[5] & Diana Bajare[6]

Buildings are energy- and resource-hungry: their construction and use account for around 39% of global carbon dioxide emissions; they consume around 40% of all the energy produced; they are responsible for over 35% of the EU's total waste generation; and account for about 50% of all extracted (fossil) materials. Therefore, they present a significant challenge to meeting national and international Net Zero targets of reducing greenhouse emissions and fossil resource use. The CircularB Project, is at the heart of this issue, which will underpin synergies of multi-scale circular perspectives (from materials, to components, to assets and built environments), digital transformation solutions, data-driven and complexity science, stakeholder behavioral science, and interdisciplinary capabilities towards achievable, affordable and marketable circular solutions for both new and existing buildings, for sustainable urban design, and for circular built environments across Europe. This paper contributes to the project by deriving new insights into the stakeholders' influences, inter-relationships, and obstacles in the implementation of circular economy concepts on existing building stocks in Europe, which represent over 90% of whole building assets. In order to identify and derive the insights, our study is rigorously based on (i) a robust critical literature review of key documentations such as articles, standards, policy reports, strategic roadmaps and white papers; and (ii) interviews with relevant stakeholders and decision makers. Uniquely, our work spans across all scales of CE implementation from materials, to products and components, to existing building stocks, and to living built environments. The findings point out the current challenges and obstacles required to be tackled. Inadequacies of financial incentives and governmental enforcement (via policy, legislation, or directive) are commonly found to be the most critical obstacles found throughout Europe. Circular economy is the global challenge and not just a single country can resolve the climate issue without the cooperation of other countries. The insights thus highlight the essential need for harmonized actions and tactical/pragmatic policies promoted and regulated by the European Commission, national and local governments who can dominate the influence, promote inter-relationship, and overcome the barriers towards circular economy much more effectively.

Keywords Circular economy, Stakeholder engagement, Stakeholder influence, Interrelationship, Obstacles, Barriers, Circular buildings, Circular materials, Sustainable assessment, Business models, Life cycle perspective

The European Commission has recently reported that, by 2050, the world will exploit tripple of today's resource demand. In the next 40 years, the world consumption of key materials such as biomass, fossil fuels, metals and

[1]Department of Civil Engineering, University of Birmingham, Birmingham B15 2TT, UK. [2]SRH Berlin School of Technology, Ernst-Reuter-Platz 10, 10587 Berlin, Germany. [3]Department of Forest Industry Engineering Faculty of Forestry, Karadeniz Technical University, 61080 Trabzon, Turkey. [4]Avoin Association, Helsinki, Finland. [5]BALTECH Study Centre, Faculty of Engineering Economics and Management, Riga Technical University, Kipsalas Street 6A, Riga 1048, Latvia. [6]Institute of Materials and Structures, Faculty of Civil Engineering, Riga Technical University, Kipsalas Street 6A, Riga 1048, Latvia. ✉email: s.kaewunruen@bham.ac.uk

buildings

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Article

Cultivating Sustainable Construction: Stakeholder Insights Driving Circular Economy Innovation for Inclusive Resource Equity

Ferhat Karaca [1,*], Aidana Tleuken [1], Rocío Pineda-Martos [2], Sara Ros Cardoso [3], Daniil Orel [4], Rand Askar [5], Akmaral Agibayeva [1], Elena Goicolea Güemez [3], Adriana Salles [5], Huseyin Atakan Varol [4] and Luis Braganca [5]

[1] Department of Civil Engineering, School of Engineering and Digital Sciences, Nazarbayev University, Astana 010000, Kazakhstan; aidana.tleuken@nu.edu.kz (A.T.); aakizhanova@nu.edu.kz (A.A.)
[2] Departamento de Ingeniería Aeroespacial y Mecánica de Fluidos, Escuela Técnica Superior de Ingeniería Agronómica, Universidad de Sevilla, Ctra. de Utrera, km. 1, 41005 Sevilla, Spain; rpineda@us.es
[3] ICATALIST S.L., Environmental Consulting Company, Calle Jacinto Benavente, 2A, 28232 Las Rozas de Madrid, Spain; sros@icatalist.eu (S.R.C.); egoicolea@icatalist.eu (E.G.G.)
[4] Institute of Smart Systems and Artificial Intelligence (ISSAI), Nazarbayev University, Astana 010000, Kazakhstan; daniil.orel@nu.edu.kz (D.O.); ahvarol@nu.edu.kz (H.A.V.)
[5] ISISE, ARISE, Department of Civil Engineering, University of Minho, 4800-058 Guimaraes, Portugal; id8641@alunos.uminho.pt (R.A.); adriana@civil.uminho.pt (A.S.); braganca@civil.uminho.pt (L.B.)
* Correspondence: ferhat.karaca@nu.edu.kz

Abstract: Due to its intricate production processes, complex supply chains, and industry-specific characteristics, the construction industry faces unique challenges in adopting circular economy (CE) principles that promote resource equity. To address this issue, this study aims to delve into identifying stakeholders' opinions and perceptions regarding key CE strategies across different stages of the building life cycle (BLC). Both European and non-European stakeholders within the "CircularB" COST Action network and beyond participated in this research. Three methods were employed to assess stakeholders' opinions: an online survey, a structured survey with a semi-guided workshop, and creative thinking round table discussions. Natural language processing (NLP), specifically topic modelling and sentiment analysis, was used to analyse the data collected from the online survey, which gathered text-based opinions from 209 participants on the cost-benefit aspects of circularity strategies. The structured survey, which collected data from 43 workshop participants, evaluated the perceived importance of CE strategies across various BLC phases and assessed the adoption of selected CE strategies in current or past projects. Finally, the Six Thinking Hats® activity, employed in the round table discussions, generated ideas from 25 professionals regarding the broader implementation challenges and opportunities of CE in construction. The research findings highlight the need to bridge the gap between theory and practice by fostering active industry stakeholder involvement in the transition to a CE model. The analyses of the collected stakeholder opinions through the three activities contribute to proactive and collaborative efforts aimed at advancing resource equity in the construction sector and promoting just and inclusive resource use. In summary, this research offers a comprehensive understanding of stakeholders' opinions on CE strategies and provides guidance for the development of targeted policies and strategies to accelerate the integration of CE principles in the construction industry.

Keywords: stakeholder perception; sustainability; industry analysis; NLP; cost-benefit analysis; circular economy

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1. Introduction

The construction industry is known to be conservative. Therefore, it is essential to acknowledge and consider the opinions and perspectives of stakeholders, especially

applied sciences

Article

Challenges of Engineering Skillsets Essential for Driving Circularity of Smart Cities

Benjamin Neale [1], Sakdirat Kaewunruen [1,*], Dan Li [2], Ayfer Donmez Cavdar [3], Rand Askar [4], Tatjana Tambovceva [5] and Diana Bajare [6]

1 Department of Civil Engineering, University of Birmingham, Birmingham B15 2TT, UK; bxn165@alumni.bham.ac.uk
2 School of Urban Construction and Safety Engineering, Shanghai Institute of Technology, Shanghai 201418, China; danli1992@sit.edu.cn
3 Department of Forest Industry Engineering, Faculty of Forestry, Karadeniz Technical University, 61080 Trabzon, Türkiye; adonmez@ktu.edu.tr
4 Institute for Sustainability and Innovation in Structural Engineering (ISISE), Department of Civil Engineering, University of Minho, 4800-058 Guimaraes, Portugal; rand.askar@hotmail.com
5 Governance and Security Institute, Faculty of Engineering Economics and Management, Riga Technical University, Kalnciema Street 6-506, 1048 Riga, Latvia; tatjana.tambovceva@rtu.lv
6 Institute of Materials and Structures, Faculty of Civil Engineering, Riga Technical University, Kipsalas Street 6A, 1048 Riga, Latvia; diana.bajare@rtu.lv
* Correspondence: s.kaewunruen@bham.ac.uk; Tel.: +44-(0)-121-414-2670

Abstract: This study aims to define specific transferable engineering capabilities needed for the implementation (design and practices) of circular economy (CE) within a smart city setting. We conducted a critical literature review of over 100 studies on the core values of CE and smart cities to investigate the knowledge gap in this topic and understand what specific skillset is employed by industry experts that can be harnessed on a wider scale, which can allow for the optimization of CE. There is a lack of research on the skillsets needed to implement a circular economy in any setting, and there are very few studies on circularity practices in a smart city setting. Primary data collection allows us to bridge this knowledge gap, yielding new findings that do not already exist concerning the skillset employed by experts in the field, which can positively impact the smart city settings in which a circular economy is implemented. We conducted a qualitative analysis based on expert interviews of 21 participants who have experience in the circular economy. This information will benefit the industry by informing businesses and councils about the key skillsets and capabilities to look out for when employing people to implement any aspect of circular practices in a smart city setting, with an emphasis on enhancing efficiency, achieving deliverables, and thinking systemically to address complex challenges they may face during the implementation. We also investigated the implementation of CE in smart cities to provide a well-rounded view of the different achievements and challenges faced during the process. This mainly focuses on the work of governance in smart circular cities, a factor that has many important implications and externalities in different sectors. This study describes the methodology adopted to formulate a detailed questionnaire for expert interviews with respect to the skill gap and capabilities necessary for working in the industry, the results of which aid discussions regarding the different challenges faced in CE implementation. Our findings reveal that background knowledge in engineering and sustainability is the most 'highly critical' hard skill according to the experts, while communication and stakeholder engagement are the essential soft skills required to ensure the success of a circular economy within smart city settings.

Keywords: engineering education; technical competency; skillset; transferable capability; circular economy; smart city; built environment; expert interviews; grounded theory

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CivilEng

Article

Synergic Co-Benefits and Value of Digital Technology Enablers for Circular Management Models Across Value Chain Stakeholders in the Built Environment

Sakdirat Kaewunruen [1,2,*], Charalampos Baniotopoulos [1,3], Patrick Teuffel [4], Hamza Driou [5], Otso Valta [6], Jan Pešta [7] and Diana Bajare [8]

[1] Department of Civil Engineering, University of Birmingham, Birmingham B15 2TT, UK; c.baniotopoulos@bham.ac.uk
[2] Shanghai Key Laboratory of Rail Transit Structural, Durability and System Safety, Tongji University, Shanghai 201804, China
[3] Department of Civil Engineering, Leibniz University Hannover, Welfengarten 1, 30167 Hannover, Germany
[4] School of Engineering, SRH Berlin University of Applied Sciences, Sonnenallee 221, 12059 Berlin, Germany
[5] SNCF Research, Route des Petits Ponts, 93600 Aulnay-Sous-Bois, France
[6] Avoin, Rantakatu 9 A 7, 06100 Porvoo, Finland
[7] University Centre for Energy Efficient Buildings, Czech Technical University in Prague, Třinecká 1024, 273 43 Buštěhrad, Czech Republic
[8] Institute of Sustainable Building Material and Engineering Systems, Faculty of Civil and Mechanical Engineering, Riga Technical University, Ķipsalas iela 6a, LV-1048 Riga, Latvia
* Correspondence: s.kaewunruen@bham.ac.uk; Tel.: +44-(0)-121-414-2670

Abstract

It is undeniable that digital technology enables, e.g., building information modelling, digital twins, extended reality (i.e., virtual reality, augmented reality, mixed reality), and automation, have recently played a significant role in the construction and engineering industry. The traditional applications of digital technologies include design and construction management, waste management, and, to a limited extent, asset management. Despite some applications of digital technologies, the technology users are often isolated and siloed. In reality, the cross-functional applications, roles, and co-benefits have not been thoroughly understood or well demonstrated. This is evident by a very limited usage of such technology across either the whole lifecycle or the value chain of built environment sectors. On this ground, this study is the first to tackle the challenges by conducting expert and stakeholder interviews using open-ended questionnaires both online and offline ($n = 42$) to identify synergic roles and influences, as well as co-benefits of digital technology enablers. Industry participants are dominant in our study and, unsurprisingly, siloed practice can undermine cross-collaboration among value chain stakeholders. Clearly, co-benefits may hypothetically occur, but they can be only unlocked by genuine, participative stakeholder engagement. This study is unprecedented, and our new findings also reveal technical and societal capabilities of digital technologies, which can inclusively enable participative decision-making, engagement, and integration of stakeholders for implementing buildings' circularity through viable business and management models. New insights clearly exhibit that digital technology enablers must be co-created by main stakeholders in order to yield co-benefits and harvest synergic value for circular management models in the built environment.

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