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Research into Modern Methods of Producing Energy-Efficient Building Materials

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Abstract
The study is devoted to the analysis of modern methods of production of energy-efficient building materials. A broad review of statistics on the level of emissions of harmful substances and the popularity of various energy-efficient materials was carried out, which made it possible to identify the environmental factor as the most vulnerable. Analysing the United Nations (UN) recommended measures to reduce CO2 emissions from the production of building materials and the amount of CO2 emissions in different countries, cement, steel and aluminium add 2.5 billion tonnes of CO2. In comparison, brick and glass production adds approximately 1.2 billion tonnes of CO2 annually. The problem of producing materials more adapted to regional peculiarities, such as insulation made from local natural materials, is considered in the example of Kyrgyzstan. Modern methods of building materials production in Ukraine include, for example, improving the quality of cement, the use of green energy and the production of Portland cement clinker. The use of waste in construction is an important step towards sustainability and environmental efficiency. This is especially true for ergonomic construction, where waste management reduces the negative impact on the environment and reduces natural resource consumption. Despite advances in construction technology and the introduction of alternative materials, bricks remain one of the most common materials. India is a leader in this area, although a study of its statistics revealed that due to the global prevalence of informal production practices, accurate statistics are difficult to collect. All sub-sectors of the ceramic industry are energy-intensive due to the need for drying and sintering at high temperatures (800-2000°C), which requires significant energy resources. Sustainability-oriented solutions and technology substitution are proving to be key to the decarbonisation of the ceramic industry. The combination of different technologies and approaches provides significant benefits in reducing CO2 emissions and energy consumption. The study results are relevant for the development of recommendations for the integration of environmentally friendly, innovative and ergonomic methods of production of energy-efficient building materials.

Keywords: Ceramics, Decarbonisation, Electrification, Industry, Emissions.

1. Introduction

Climate change and the depletion of natural resources require new approaches in the construction industry, which has a significant impact on the environment, with greenhouse gas emissions associated with the production of building materials and significant energy consumption during their manufacture contributing to global warming and environmental pollution. The research relevance is determined by the need to reduce the negative impact of the construction industry on the environment at the production stage through the implementation of the latest technologies. In the context of growing environmental awareness and international commitments to reduce carbon emissions, there is an urgent need to introduce new, more energy-efficient and environmentally friendly building materials. The introduction of energy-efficient technologies in the production of construction materials is an important step towards increasing their demand and competitiveness. This reduces energy and resource costs, greenhouse gas emissions and waste. Companies that use such technologies can gain financial benefits and meet modern environmental standards, which helps to expand their customer base and strengthen their market position.

In the context of the study of modern production methods in the construction industry, it is necessary to first determine which aspects have a negative impact on this process, as well as the accompanying consequences that determine the impact of the construction industry on the environment and economic processes. Marut et al. (2020) studied the use of alternative building materials for sustainable construction by assessing the reduction of the environmental impact of construction and promoting sustainable development by providing environmentally friendly and sustainable buildings. Adrees et al. (2016) highlighted that gas emissions from brick kilns decrease the air quality in Pakistan and around the world. Alqahtani et al. (2023) highlighted that the operational energy used during the life cycle of a building accounts for 60-80% of the total energy, with the rest coming from the embodied energy of materials. When studying modern methods of producing energy-efficient building materials, researchers face several key challenges. The technical feasibility of using industrial technogenic waste in the construction industry to produce new energy-efficient materials is one of the key factors in developing modern methods of environmental and economic improvement of construction materials production. Lemeshev et al. (2020) highlighted that the most important area of phosphogypsum waste utilisation is its use in the production of building materials, as it consists of 80-95% calcium sulphate, which makes it suitable for use as gypsum raw materials. Thakur et al. (2018) investigated the potential of using marble waste to create environmentally sustainable composite materials for construction. Huang et al. (2023) also investigated how preliminary chemical treatment, resin impregnation and compaction of wood at the stage of manufacturing high-performance wood composites using natural fast-growing massive pine affects the increase in strength and durability of fast-growing wood, thus using it as a structural material in extreme conditions. As emphasised by Wiik et al. (2018), Abobakirov and Omonboev (2023), in addition to waste recycling, it is also necessary to use renewable natural materials and resources for energy generation and to expand the possibilities of replacing harmful components in building materials. The need to focus research on reducing greenhouse gas emissions in construction using low-carbon materials is emphasised. For instance, bio-based materials such as bamboo, hemp, straw bales and mycelium composites are being used as sustainable alternatives to traditional building materials, providing low embodied energy and reduced environmental impact.

However, there are some gaps in research in this area. While electrification of production processes has the potential to reduce CO_2 emissions, more research is needed on its impact on overall energy costs and infrastructure requirements. The study aims to assess the negative aspects that arise in the production of energy-efficient building materials to find sustainable and effective solutions to improve this process. It is necessary to determine how the introduction of new materials and technologies affects local communities and economies, and most studies do not address the regional context. It is also necessary to address how changes in certain material properties during the implementation of a new production method affect changes in its characteristics and whether they meet its functional requirements.

Research of modern methods of producing energy-efficient building materials is a complex task that must cover many factors and features, as well as overcome various methodological and practical issues. The main objectives of the study are to assess the development of energy-efficient building materials from secondary and renewable resources, as well as to determine the impact of innovative technologies on reducing energy costs and greenhouse gas emissions in the construction industry.

2. Materials and Methods

The systematic analysis identified the main areas of modern high-tech production of energy-efficient building materials using the latest technologies. As such, publications and scientific articles from reputable international journals on architecture, construction and design were analysed. The efficiency of different methods of building materials production was compared by analysing the amount of CO_2 emissions and other chemical processes, based on laboratory experiments by other scientists. Data on the qualitative characteristics of various materials, such as strength, thermal conductivity, durability and fire resistance, were employed. All this was used to analyse the compliance of a particular material with energy efficiency requirements. The article analyses the climatic conditions, availability of natural resources and specifics of housing construction in Kyrgyzstan and collects data on local insulation practices. Data from the global data and business intelligence platform Statista (2024) was used for the objective analysis.

The materials of the United Nations (UN) were also studied, namely the latest Global Status Report for Buildings and Construction (2024). This document covered the issue of harmful environmental emissions and the importance of using certain materials to achieve the goals of the Paris Agreement to reduce carbon by 50% by 2030. In addition to the above, among the publications under the auspices of the UN, Indian Third Biennial Update Report to the United Nations Framework Convention on Climate Change (2021) was also considered. Electrification was considered one of the newest methods of transition to low-carbon production. The study also employed a report by the United Nations Environment Programme and the Yale Centre for Ecosystems + Architecture (2023), which was used to identify the main measures recommended for implementation by various participants in the construction materials production process.

The activities of the Ukrainian-American company Kwambio, dedicated to the production of three-dimensional parts using 3D Metal Printing technology, patented in 2014, were relevant to the study. To determine the importance of 3D printing technologies, the facade of a garage in Huntsville was analysed (3D Printing Technology..., 2021). Life cycle tools for various building materials were also analysed, with the American Iron and Steel Institute playing a significant role in their development (Sustainability in steel recycling..., 2020). The information obtained provided an understanding of the life cycle of steel when it is recycled and the environmental benefits of this process. The data from the Global Cement and Concrete Association, which is an authoritative platform related to the production of building materials such as cement and concrete, was carefully researched. This was used to identify the most progressive countries in terms of regulatory frameworks and innovative technologies in the field of low-carbon concrete (Policy developments for..., 2024).

An analysis of global experience in terms of the level of pollution impact resulting from highly energy-intensive building materials production processes helped to identify the most optimal materials, their combinations, and chemical and physical processes that stimulate energy efficiency and have a lower environmental impact.

3. Results

The production of construction materials belongs to the industrial sector of the economy, in particular to the sub-sector of non-metallic mineral products, and the production of construction materials is an important component of the industrial sector, as it provides basic materials for the construction industry, which plays a key role in economic development and infrastructure provision. In 2022, industry accounted for 28.04% of economic sectors in the global gross domestic product (GDP) (Global Status Report for..., 2024). CO_2 emissions from building and construction activities reached new peaks in 2022, reaching almost 10 billion tonnes of CO_2, mainly due to building operations and materials production. Emissions from electricity use increased to 6.8 billion tonnes of CO_2, while direct emissions from buildings decreased slightly to 3 billion tonnes of CO_2. The production of materials such as cement, steel and aluminium added another 2.5 billion tonnes of CO_2, while brick and glass production added approximately 1.2 billion tonnes of CO_2. Energy intensity per square metre increased by 3.5% from 2021 to 2022 due to better building codes and material performance, especially in colder climates. However, many countries do not yet have building energy codes, so the pace of modernisation needs to increase significantly to meet the Paris Agreement goal of reducing carbon emissions by 50% by 2030 (India Third Biennial Update... 2021).

The environmental impacts of building materials and mitigation approaches need to be assessed through a life cycle approach to avoid strategies that may mitigate environmental impacts at one stage but may have more negative impacts at other stages of life. The life cycle of construction materials includes several stages, starting with the extraction of raw materials, their processing and production, further transportation, construction and modernisation, as well as use, maintenance, demolition and waste management. Another important aspect is waste management and recycling through the reuse, recycling and recovery of materials. Life cycle analysis (LCA) is a method of assessing the potential environmental impact of a product (Huang et al., 2020). Among the industrial sectors that can significantly save energy, it has been identified as one of the key sub-sectors in the industrial sector aimed at reducing energy consumption. Ceramics have a wide range of applications, including technical (heat and shock-resistance), electronic (capacitors, insulators, lithium-ion batteries and microwave devices), architectural and white goods (Ibn-Mohammed et al., 2019). Ceramic materials have a high thermal insulation capacity, which keeps the room warm in the cold season and reduces heating in the summer. This reduces the energy required for heating or cooling the building. In addition, they are highly resistant to fire, have a long service life and are resistant to external factors such as humidity, UV radiation and corrosion. Hence, buildings constructed with ceramic materials can last for many years without the need for significant repairs or replacements. This durability reduces the energy costs associated with building repairs and maintenance.

India is one of the leaders in brick production, but according to the India Third Biennial Update Report to the United Nations Framework Convention on Climate Change (2021), the brick industry consumes very little energy in this sector. However, there are significant discrepancies in the estimates of fuel consumption in this area, with the figures from the report differing from expert studies by a factor of 10-100. These differences in energy consumption can be explained by several factors. Firstly, incomplete accounting by official sources. In practice, official statistics rely on coal supply data to estimate industrial use. However, the brick industry in India is highly unorganised and the actual supply and consumption of coal is not fully reported. In addition, the industry uses biomass fuel, which comes from local sources and is not accounted for in official documents. Secondly, the lack of official production data also complicates the assessment (Tibrewal et al., 2023). All areas in the ceramic industrial sector require a large amount of energy due to the need for drying and subsequent sintering at high temperatures, which typically range from 800°C to 2000°C. Sintering is a form of heat treatment that involves pressing a powder to impart strength and integrity. It is the procedure of compacting and shaping a solid mass of material using heat or pressure without melting to the point of liquefaction. Determining the potential technical and economic impact of sintering methods, production routes and composite materials is essential, and it is critical that this understanding begins at the design and/or laboratory stage, rather than after they have been fully expanded or used

The ceramic industry has received particular attention in decarbonisation efforts, with the European ceramic industry emitting around 19 million tonnes of $_{CO2}$ annually, representing approximately 1% of total industrial emissions in Europe covered by the European Emissions Trading System (ETS). Ceramics production is a small emitter, accounting for 10% of all industrial installations included in the ETS. The emissions associated with ceramics production can be divided into three main categories: combustion of fuels for drying and heating processes, process emissions arising from the mineralogical transformations of clay, and indirect emissions, mainly from electricity used in production. Based on this, measures have been developed that can be combined to reduce process emissions. These include reducing the carbon content of additives, minimising/optimising the carbon content of clay mixtures while ensuring that transport-related emissions do not increase, as well as dematerialisation (using less raw materials for the same output) and the use of carbon removal technologies and offsetting measures (Ceramic Roadmap to 2050, 2021). The use of ceramic waste in construction materials such as screeds and cement are an effective way to reduce environmental impact and optimise resource use. Ceramic waste can be used as a substitute for river sand and as aggregates for concrete, which increases its strength and durability. The use of this waste also reduces the fuel and energy consumption and CO_2 emissions associated with cement production. Ceramic waste can improve the quality of concrete and reduce its vulnerability to fire and frost. For instance, their use maintains the strength of concrete structures after exposure to fire or frost. In addition, the use of ceramic waste in concrete production reduces its water permeability and increases its resistance to abrasion (Del Rio et al., 2022).

One of the most promising approaches to modernising construction production is the cost-effective electrification of industrial equipment, which also serves as a means of switching fuels. In addition, electrification is a form of energy efficiency, as it reduces energy consumption, emissions and costs (Electrification and Efficiency..., 2019). Improving the efficiency of existing electrical equipment, such as motor drives and compressed air systems, also reduces energy demand and energy-related CO_2 emissions. Reduced energy demand reduces the required size of capital equipment, which reduces the cost of introducing new electrical technologies. Managing the energy efficiency of raw materials, waste streams and recycling reduces the cost of decarbonisation in heavy industry by around 40%. The drive towards electrification should be accompanied by efforts to increase low-carbon generation so that electrification becomes increasingly profitable. In addition, it is necessary to promote the connection of industrial users to electricity to facilitate adaptation, increase capacity and ensure reliability. Cross-cutting and sectoral applications of useful electrification provide opportunities for expanding the use of electrical technologies in industrial subsectors (Rightor et al., 2020).

Electrification of the production of building materials such as cement, steel and glass significantly reduce carbon emissions. The use of electricity from low-carbon sources instead of fossil fuels reduces the amount of CO_2 emitted during the production of these materials. The introduction of electrified technologies, such as electric furnaces or induction heaters, increases the energy efficiency of production processes. Electric technologies often have a higher efficiency than traditional fossil fuel technologies. Electrification contributes to the development of new materials and production processes that are more energy efficient. For instance, the use of electrical technologies is stimulating the creation of new building material compositions with improved thermal insulation properties. The production of heat-insulating building materials and the improvement of their thermal insulation properties is the most promising for production in terms of the life cycle of a building. By investing in the purchase of a material with these characteristics, an investor can invest more in the purchase of an environmentally friendly, but more expensive material. However, within a few years, it smoothly covers its cost due to significant energy savings during the operation of the building due to reduced maintenance costs for heating and air conditioning systems.

The need for heat for residential households in cold climates such as the high mountainous rural area of Kyrgyzstan is very high. The main reasons for this high demand for heat are the high level of heat leakage and the lack of insulation. Typically, insulation is made of petroleum-based plastics and foams such as extruded polystyrene or polyurethane foam, which are used in industry and rarely available in rural areas. The isolated location and low income of remote settlements in Kyrgyzstan are key barriers to the availability of such insulation materials (Mehta et al., 2020). When modernising the building envelope, materials and insulation costs are key parameters. There are three most common natural heaters in Kyrgyzstan: sheep wool, straw bales and reed panels. Sheep wool is a by-product of sheep production and can be used for insulation without affecting its textile quality. Wool can be simply stuffed into prepared cut-outs in the façade structure, but its use must be carefully controlled to ensure long-term sustainability. Straw is another widely available material that is a by-product of agricultural activities. It can be used for insulation in bales, which can be used as a filling material or as a load-bearing structure. The use of straw reduces the need for other building materials and helps to reduce heat loss through the building envelope, especially in cold winters. However, it is necessary to control the moisture content of the straw so that it does not exceed 15%.

Further reductions in heat demand can be achieved by optimising the material of windows and frames or by insulating roof structures, although this requires more investment. This requires an individual solution for each case. Specific strategies and measures should be developed that take into account local conditions and resources to ensure the efficient use of sustainable materials and reduce energy consumption in rural homes in Kyrgyzstan (Beringer et al., 2021). The use of aerogels, which are known for their extremely low thermal conductivity and lightness, is also promising. Although more expensive than traditional insulation, this material can significantly reduce the need for heating and is transported in compact forms. Another approach is the use of vacuum insulation panels, which provide high thermal insulation efficiency at a low thickness, making them convenient for transport and installation in difficult conditions. Spray foam technology also has its advantages, especially in hard-to-reach areas. This material can be delivered as a liquid component that, once applied to walls or other structures, expands and hardens to provide excellent insulation. Similarly, the use of modular insulation, which is easy to transport and quick to assemble on-site, can greatly simplify the insulation process. These modules are often made from environmentally friendly materials and may include innovative insulation technologies. Sustainable solutions also include the development and use of new types of insulation made from recycled materials, such as recycled glass or plastic, which have good thermal insulation properties and are more environmentally friendly. An important aspect is the development of local production facilities for the manufacture of such materials, which will reduce the need for transportation from remote regions.

Another approach is to use cellulose insulation, which is made from recycled paper or cardboard. This material is not only environmentally friendly but also effectively reduces heating costs thanks to its thermal insulation properties. An important advantage of cellulose insulation is its ability to breathe, which prevents moisture accumulation and contributes to a healthy indoor climate. The use of mushroom materials for insulation is also promising. Mushroom materials are made from mushroom mycelium that is grown on organic waste, such as sawdust or husks. This material is fully biodegradable and can be composted at the end of the service term of a building. The use of geopolymers to create insulation materials is another environmentally friendly solution. Geopolymers are made from natural minerals and can have thermal insulation properties similar to traditional insulation but without the use of petroleum products. One of the most innovative approaches is the development of bioplastics based on vegetable oils or starch. These materials have a much lower environmental impact than traditional plastics and can be used to create insulation materials. The use of energy-efficient materials also gives the investor an advantage in the construction project market, as the project can be positioned as environmentally friendly. This approach attracts the attention of customers who value environmentally friendly and energy-efficient solutions, which helps to promote sustainable construction methods among large companies. The growth in electricity demand associated with electrification is driving the development of a more stable and reliable electricity infrastructure. This is important for the production of energy-efficient building materials, as a stable energy supply is key to the smooth operation of production facilities, and it also stimulates a reduction in energy costs through increased energy efficiency, which reduces the cost of building materials production, making energy-efficient building materials more affordable for consumers, stimulating their widespread adoption. Electrification also helps building materials producers meet increasingly stringent environmental standards and regulations on greenhouse gas emissions. This ensures their competitiveness in the market.

The production of cement, sheet glass, iron, steel and other building materials in China is a major source of CO_2 emissions. China accounts for more than half of the world production of these materials, which contributes to significant greenhouse gas emissions. CO_2 emissions from the construction of civil buildings, including the production and transportation of building materials, account for a significant share of Chinese total carbon emissions, highlighting the importance of reducing emissions in this sector (Hu et al., 2022). In the context of Ukraine, one of the key areas is to reduce the clinker ratio in cement, which involves the use of alternative fuels and raw materials, as well as green energy. This not only reduces CO_2 emissions but also improves the overall environmental friendliness of cement production. As part of the development of a sustainable approach to the production of Portland cement clinker in Ukraine, much attention is paid to the use of alternative fuels and raw materials. In particular, the use of biomass and other renewable energy sources, which will have a positive impact on the total amount of CO_2 emissions per tonne of clinker, was addressed. Improving the quality of cement is another important area. The introduction of active mineral admixtures reduces the clinker ratio, which not only reduces emissions but also improves the strength and durability of concrete. This is necessary to ensure the reliability and sustainability of buildings and infrastructure (Bielohrad, 2023). Green energy plays a key role in achieving carbon neutrality goals. The use of renewable energy sources, such as solar and wind power, can significantly reduce greenhouse gas emissions from cement production. In addition, the introduction of energy-efficient technologies and optimisation of production processes helps to reduce energy consumption and improve environmental efficiency.

However, some of these solutions are not environmentally friendly due to the use of polymers. For instance, alternative polymer-based insulation materials, such as extruded polystyrene or polyurethane foam, can have a negative impact on the environment due to the complexity of disposal and the potential for toxic substances to be released during their operation and disposal. Therefore, it is necessary to consider the entire life cycle of materials and consider the use of more environmentally friendly alternatives. The goal of decarbonising the production of building materials is to find the most effective methods to improve this process, but this is impossible without considering all the factors of the service term of the building. Stimulating the development of the latest production technologies, increasing demand for new and higher quality and environmentally friendly materials, and ensuring regulatory control by the authorities contribute to building a well-established system of involving various groups of people and participants in the building life cycle in the process of reducing CO_2 emissions at the production stage (Table 1).

Participants in the construction materials production process	**Politicians**	**Financial investors and developers**	**Manufacturers, builders, waste managers**	**Architects, engineers**
Events	1. Electrification of the network. 2. Official regulation of recycling and best available technologies. 3. Official management of forests and materials. 4. Improving certification.	1. Investing in innovation for low-carbon materials and binders. 2. Investing in new low-carbon methods. 3. Investing in the best available technology.	1. Renovation of plants. 2. Avoiding basic materials. 3. Circular production and composites for reuse. 4. Regulation of fair labour.	1. Working with manufacturers to detail the circulation of materials. 2. Design development of alternative bio-based materials and components.

Table 1. Measures to Strengthen International Action and Cooperation to Collectively Impact the Decarbonisation of Building Materials during Production in the Context of the Building Life Cycle.
Source: compiled by the authors based on United Nations Environment Programme and Yale Center for Ecosystems + Architecture (2023).

Year	2015	2016	2017	2018	2019	2020	2021	2022
Total CO_2 per tonne of cement (tonnes)	0.54	0.55	0.56	0.58	0.58	0.58	0.58	0.58

Table 2. Direct Emissions Intensity of Cement Production in the Zero Net Scenario, 2015-2022.
Source: compiled by the authors based on Policy developments for reducing emissions (2024).

Approximately 7% of CO_2 emissions worldwide come from cement production. This is due to the high energy intensity of the firing process and the chemical reaction of limestone decarbonisation. Although cement is the main component of concrete that absorbs CO_2 during its life cycle, this absorption is often not considered in traditional environmental impact assessments. Cement is primarily used in ready-mixed concrete and concrete products for buildings and infrastructure that can last from 10 to 100 years. During this period, the concrete surface absorbs CO_2 from the atmosphere. At the end of the service life of a building or infrastructure, concrete is subject to dismantling and recycling. During the recycling process, concrete is crushed, creating new contact surfaces with the atmosphere, which accelerates the absorption of CO_2, confirming the need to consider the environmental impact of concrete in the context of the service term of a building. Concrete has many ways to be implemented as an energy-efficient material, especially at the production stage (Table 2).

The main challenge facing the cement industry is to reduce CO_2 emissions while meeting production needs. The infrastructure needs of emerging economies require widespread adoption of new technologies to reduce emissions in this sector. The intensity of direct CO_2 emissions from cement production remained almost unchanged from 2018 to 2022. However, to meet the target of reducing CO_2 intensity by 4% annually by 2030, the sector needs to take serious action. This is necessary to start implementing the net zero emissions scenario by 2050. In a policy analysis conducted by the World Economic Forum and the Global Cement and Concrete Association, countries such as the Netherlands, Sweden, Germany, France, the United Kingdom and the United States were recognised as leaders in establishing regulations aimed at reducing carbon emissions in the construction industry, as well as in implementing accompanying public procurement programmes (Policy developments for..., 2024).

The concept of calcium carbonate concrete is gaining relevance to address the issue of carbon dioxide emissions. In this concept, calcium carbonate, which contains calcium that comes from demolished concrete or other calcium-containing industrial waste, and bicarbonate, which is derived from CO_2 gas collected from the air or emitted by industrial plants, are used as binders for aggregates, which can be natural rocks or crushed stone from demolished concrete (Hyodo et al., 2020). The process of manufacturing calcium carbonate concrete begins with the extraction of calcium from industrial waste or demolished concrete. Calcium in the form of calcium hydroxide reacts with CO_2 captured from the air or industrial emissions to form calcium carbonate. This chemical reaction not only helps to reduce carbon dioxide emissions but also forms a strong binder for the concrete mix. The aggregates in this mixture can be natural stones or crushed concrete obtained from demolished structures. Thus, the use of calcium carbonate concrete promotes the formation of stable aragonite and calcite phases, which improves the mechanical properties of the material and reduces its carbon footprint. This makes calcium carbonate concrete a promising material for environmentally sustainable construction. This technology not only helps to reduce greenhouse gas emissions but also allows for the efficient use of waste, turning it into valuable construction materials (Maruyama et al., 2021).

Carbonation hardening of Portland cement concrete is a promising method for reducing CO_2 emissions and improving the mechanical properties of the material. The study of the reaction mechanisms that occur during the carbonation of fresh cement pastes determined the influence of curing conditions on the kinetics of reactions, phase formation and microstructure evolution. During early carbonation, alite and bilite react with dissolved CO_2. Carbonation and hydration reactions reduce pore volume and improve porosity, which resembles the development of microstructure in composite cement (Zajac et al., 2022). Carbonation strengthening of Portland cement concrete can be effectively combined with other innovative methods of building materials production to achieve more environmentally friendly and efficient results. One such method is the use of nanomaterials such as nanofibres or nanosilica. The addition of these nanomaterials to the cement mix increases its strength and durability by improving the microstructure and reducing porosity. When this method is combined with carbonation hardening, not only does the pore volume decrease but the bond between the carbonate phases and the nanoparticles is enhanced, resulting in a significant improvement in mechanical properties. Another promising approach is the use of polymeric materials formed from aluminate-silicate sources (e.g., metakaolin) as a result of alkaline activation. Geopolymers have a low carbon footprint and high mechanical properties. The integration of geopolymers with carbonisation strengthening can lead to materials with exceptional strength and durability while reducing CO_2 emissions during production.

Since the mid-1980s, along with the growth of computer control systems, 3D printing technology has gradually emerged. This new process of industrial production became an important tool for the Third Industrial Revolution. Aimed at significantly reducing resource use, labour costs and emissions, 3D printing has gained widespread attention in the construction industry. This technology involves the manufacture of parts using a “printer” or a special industrial machine that creates product shapes by applying material along a given contour. This approach is also known as “additive manufacturing” and combines mechanical numerical control, computer-aided design, rapid prototyping and other related technologies. ASTM Technical Committee F42 defines this technology as “the process of joining materials to create objects from a 3D model, usually layer by layer, as opposed to subtractive manufacturing methods”. The life cycle of a 3D-printed concrete material includes several stages, such as raw material extraction, cement and aggregate production, material transport, electricity generation, printing, construction, maintenance, and demolition or dismantling. Understanding all these processes is important to assess the potential of the technology. Mixtures for 3D-printed concrete are developed based on three material parameters: pumping, extrusion and build-up capabilities. These properties are determined by consistency, cohesion, stability and phase probability. Geopolymer binders are becoming increasingly popular for use in 3D concrete printing. Their advantage is the fast curing of the mixtures, which facilitates the printing process. The choice of binder affects the freshness of the mixtures (Bhattacherjee et al., 2021).

The Ukrainian-American company Kwambio is known for its achievements in the field of additive manufacturing. One of the most well-known projects is Chervona Khvylia PJSC in Kyiv, which produces three-dimensional parts using metal or alloy fusion, known as xBeam 3D Metal Printing. This method can be used to create products from ordinary industrial wire, simplifying the process of manufacturing parts. Chervona Hvilya has created a pilot printing system using the xBeam 3D Metal Printing technique for the first time, which allows the production of various products. They now offer a variety of printer models for both laboratory use and industrial printing of large product sizes. The xBeam 3D Metal Printing technology is a directed energy deposition process and is implemented in the form of an electron beam gun and a wire feeder. This method is similar to FDM, where the filament is applied layer by layer to create a part. Another successful example of the introduction of additive manufacturing technologies in Ukraine is Kwambio, a startup that has developed a 3D printing solution based on the binder jetting (BJ) method. This allowed them to start producing ceramic parts at their plant in Odesa at an affordable price. The technology of inkjet printing on binder materials allows for the precise reproduction of parts following the created 3D model, opening new prospects for the production of bioceramics for prosthetics. For example, the façade of a garage in the centre of Huntsville, Alabama, consists of exterior panels that take their shape using an open lattice material called BranchMatrix, printed on a 3D printer. This material can take on almost any shape, which was used to implement a complex design of the garage facade. The process of creating these facades involves 3D-printed BranchMatrix lightweight polymer moulds that are filled with 2lb of insulating foam, then robotically milled to achieve the required geometric surface, and finished with a coating of glass fibre-reinforced concrete. The result is a lightweight, energy-efficient and durable building facade (Sustainability in steel recycling, 2020).

The use of recycled brick aggregate has significant potential in developing countries, such as South Africa, where brick construction is widespread and landfill space is limited. Adding this recycled material to the 3D printing mix requires a higher volume of water in the mix to achieve the required characteristics due to the water absorption properties of the brick aggregate. This also requires careful design of the mix composition to achieve maximum material density, but with increasing porosity, the strength of the concrete may decrease. Thus, the addition of highly porous recycled brick aggregate to the concrete mix can lead to a decrease in its strength (Christen et al., 2022). There is a misconception that recycled steel is more environmentally friendly than virgin steel. However, in the context of sustainable development, steel must be reused or recycled at the end of its service life. This means that the steel can be completely recycled into a new material with no loss of quality or strength. The International Iron and Steel Institute has developed life cycle assessment tools to help understand the benefits of steel recycling (Sustainability in steel recycling, 2020). Steel recycling is an effective way to avoid the negative environmental impacts associated with the extraction and production of steel from primary raw materials. The importance of recycling and reusing steel at the end of its service life is critical to ensuring the sustainability of the material. If the entire content consists of recycled steel, this has no impact on the sustainability of the application in a life-cycle context. An important aspect of steel recycling is the efficient sorting and processing of scrap, especially end-of-life (EOL) scrap. Moulding and production scrap usually have a low level of contamination and can be recycled without significant accumulation of impurities. However, EOL scrap often contains various impurities, which makes it difficult to recycle (Harvey, 2021).

Steel is processed through several methods, and there is no single best way to process steel, as each has its unique advantages and applications depending on specific requirements and production conditions, but one of the most common is the electric arc furnace (EAF) process. First, steel waste is collected, which can include EOL scrap, moulding scrap and production waste. The collected scrap is sorted by type and quality. This step is necessary to separate recyclable material from unsuitable material. The sorted scrap is prepared for melting. This includes cutting, crushing or other operations to facilitate melting. The prepared scrap is melted in the EAF, which is powered by a large amount of electrical energy. Under the influence of high temperature, the electrodes melt the scrap, turning it into liquid steel. After melting, various alloying additives can be added to the liquid steel to obtain the required chemical composition and properties of the steel. Liquid steel is poured out of the furnace and into moulds to form the final products. The resulting products are cooled and subjected to various processing operations, such as rolling, drawing, forging or machine tooling, to give them the required shape and properties. The electric arc furnace process is a fast, efficient and environmentally friendly way to produce steel, as it uses secondary steel and does not require large volumes of primary iron ore.

Moreover, for example, the BOF process uses air converters to melt the feedstock material, which can be coal or gas, together with iron ore. This method effectively removes carbon and some other impurities from raw materials. The electric arc furnace method is widely used for the production of large volumes of steel, especially for the production of lightweight and structural steel. It quickly melts waste metal and uses different energy sources to melt metal. The steel industry is also using a circular economy (CE) to reduce CO_2 emissions, which involves closing material cycles and creating industrial symbiosis. CE uses secondary resources, such as steelmaking waste, to produce steel and other materials. Also known as sustainable carbon use (SCU), it involves the efficient use of carbon as an energy source and a renewable resource in the steel production chain. This includes the use of carbon from non-steel industries and secondary sources.

Achieving climate neutrality goals by modernising construction materials production methods is not a task that can be accomplished by industry alone. This is a complex and multidimensional process that requires the influence of other areas of society and the international community. Effective climate change mitigation requires a proper regulatory framework that encourages businesses to adopt environmentally friendly technologies and production processes. This may include the establishment of mandatory environmental safety standards and the introduction of environmental certification systems and mechanisms to encourage environmental innovation. It is necessary to ensure fair conditions for all economic actors, including industry. This means developing policies to reduce environmental inequalities and implementing social and environmental standards that protect the rights of workers and local communities. Access to finance plays an important role in the transition to environmentally sustainable technologies and processes. The industry requires financial support to implement green investments and improve environmental practices. The development of new technologies, such as renewable energy, hydrogen technologies and the circular economy, is a key element in achieving climate neutrality goals.

Achieving climate neutrality requires a comprehensive approach that encompasses various sectors of society and requires global cooperation and coordination. Industry plays an important role in this process, but success depends on the joint efforts of all stakeholders. Climate neutrality goals cannot be achieved by the industry alone. Achieving such goals depends on external factors beyond the industrial control, such as an appropriate regulatory framework, a level playing field, access to finance, new technologies and decarbonised energy.

4. Discussion

The study analysed the production processes of modern building materials and identified those with the greatest potential for energy efficiency, such as bricks or thermal insulation materials. The use of waste from the production of other building materials in the manufacture of new ones, as well as their use as an environmentally friendly alternative in the production of long-established materials, was particularly important for achieving the decarbonisation goals of sustainable construction. 3D printing technology, including additive manufacturing, is an important tool for industrial production, especially in the construction industry, due to its advantages in reducing resource and labour costs, as well as reducing greenhouse gas emissions. The Ukrainian-American company Kwambio is known for its achievements in additive manufacturing, including the creation of ceramic parts using the technology of step printing on binder materials. Another successful example of 3D printing is a garage facade project in Huntsville, Alabama, where BranchMatrix lightweight polymer moulds printed on a 3D printer are used. The use of recycled brick aggregate in the mix for 3D printed concrete has significant potential but requires careful sorting of the mix and affects the strength of the concrete by increasing porosity.

Federowicz et al. (2023) developed a set of heavyweight concrete for 3D printing, replacing 40% or more of river sand with magnetite. This made it possible to meet the requirements of EN 206-1 for the classification of the material as heavy concrete. The inclusion of magnetite in the mix did not significantly affect the fresh properties of the mix, and all mixes met the printing requirements with minor changes in the superplasticiser dosage. The strength study showed that the combination of natural sand and magnetite provided the highest strength, although the magnetite blend had similar or even lower characteristics than the control blend. This study also reveals the possibility of changing the characteristics of 3D-printed concrete by adding recycled materials to it. This highlights the possibility that it can acquire new physical characteristics depending on the type and amount of a particular material. The current study focuses on exploiting the possibility of using 3D printing as a recycler of construction waste. This study does not provide any specific recommendations on the application of such material. Awal and Mohammadhosseini (2016) also investigated the use of recycled materials, but not in the context of 3D printing, identifying palm oil fuel ash that can be used effectively in construction. It is produced from the combustion of palm oil residues and has significant potential to improve concrete properties and can also be used as an additional cement material, which reduces the need for traditional cement and reduces CO_2 emissions.

Llantoy et al. (2020) studied modern methods of producing energy-efficient building materials in the context of LCA, they emphasised the importance of considering the environmental impact and energy consumption at the production stage. Traditional insulation materials such as polyurethane and polystyrene, while helping to reduce energy demand, have a high environmental impact, especially during the production phase, which involves industrial and chemical processing of raw materials. This high impact manifests itself in the form of various emissions and waste that affect human health and ecosystem quality. These findings resonate with the fact that assessing impacts at individual stages can lead to shifting problems from one stage of the life cycle to another. LCA helps to avoid this by weighing all aspects of environmental impact and identifying only those methods of production modernisation that are effective in tandem with all stages of construction.

The ceramic sub-sector of the construction materials industry is one of the most energy-intensive industrial sectors with great potential for efficiency gains through modern energy reduction technologies. Ceramics have a wide range of applications, including technical, electronic, architectural and household products, which are characterised by high thermal insulation, fire resistance and resistance to external factors. Emissions can be divided into three categories: emissions from fuel combustion, process emissions from clay mineralogical transformations, and indirect emissions from electricity use. To reduce process emissions, measures such as reducing the carbon content of additives, optimising clay mixtures, dematerialisation, carbon removal technologies and offsetting measures are proposed. The use of ceramic waste in construction materials such as screeds and cement is an effective way to reduce environmental impact and optimise resource use. Ceramic waste can replace river sand and aggregates for concrete, which increases the strength and durability of building materials, as well as reduces fuel and energy consumption and CO_2 emissions associated with cement production. The use of ceramic waste improves the quality of concrete, reduces its water permeability and increases its resistance to fire and frost while maintaining the strength of concrete structures after exposure to these factors.

Samadi et al. (2020) also conducted a study on this topic, which showed that the use of ceramic waste as a partial replacement for cement and fine aggregates in mortars significantly improves their mechanical properties and durability. The use of this waste reduces environmental impact, promotes energy efficiency and reduces construction costs. This topic was also addressed by Bisht and Neupane (2015), after analysing soil samples taken at different distances from the brick kiln, found that soil quality improves with distance from the brick kiln, so soil quality is proportional to the distance from the brick kiln. This highlights the need to modernise ceramic production through the introduction of new technologies. Both studies highlight the importance of using ceramic waste in the production of construction materials such as cement and concrete, which reduces the environmental impact of reusing waste that would otherwise become part of landfills. This not only reduces waste but also saves natural resources used in the production of new materials. In addition, the use of ceramic waste improves thermal insulation properties, which reduces the energy required for heating and cooling buildings. In the ceramics sub-sector, technological improvements are aimed at increasing the efficiency of production processes, in particular reducing energy consumption during the drying and sintering of materials.

Electrification significantly reduces CO_2 emissions by replacing fossil fuels with electricity from low-carbon sources such as wind and solar. This approach contributes to the development of a more stable and reliable electrical infrastructure, which is a key aspect of the production of energy-efficient building materials. This topic was also studied by Farnsworth et al. (2018), emphasising the importance of electrification in industry for reducing CO_2 emissions and energy efficiency, electrification can significantly reduce energy demand and associated CO_2 emissions, and increase the stability and reliability of the electrical infrastructure. Both studies support the idea that electrification can significantly contribute to reducing CO_2 emissions and improving energy efficiency in various industrial and building sectors. Both emphasise the importance of developing low-carbon electricity sources and creating a stable and reliable electricity infrastructure to support this process.

The study of the above-mentioned scientific works and their comparison with the conducted research identified the main trends in the formation of modern methods of construction of energy-efficient materials. The discussion emphasises the importance of using 3D concrete printing technology using a mixture of recycled materials and available analogues such as magnetite. It also highlights promising methods for improving the production of ceramic materials in terms of ergonomics. The impact of electrification of the construction sector on reducing energy consumption and CO_2 emissions is also discussed.

5. Conclusions

This study considers various methods of modernisation and qualitative improvement of various aspects of the production of energy-efficient building materials in terms of environmental impact and reduction of energy intensity of this process. The study results showed that recycling, decarbonisation and the use of digital or energy-efficient technologies play a key role in improving the production system in this industry. Although energy-efficient materials may be more expensive to produce, the purchase of such materials provides significant economic benefits during the life of the building. The production of thermal insulation materials for housing in the mountainous regions of Kyrgyzstan requires an individual approach, such as the use of local natural materials, cellulose insulation, aerogels, and the development of bioplastics based on vegetable oils or starch.

The ceramic industry is important for both human development and the environment. However, the industry is also responsible for a significant portion of CO_2 and other pollutant emissions. The study points to the need to develop decarbonisation strategies for the ceramic industry to reduce its impact on the environment and society. Traditional methods of sintering ceramics that require high temperatures consume significant amounts of energy, cold sintering is an alternative for many materials, allowing them to be sintered at room temperature up to 200°C, this method significantly reduces energy consumption and carbon emissions, making it environmentally and economically viable. The use of ceramic waste in building materials brings significant benefits from both an environmental and economic perspective. The electrification of building materials production significantly reduces carbon emissions by replacing the use of coal and other fossil fuels with the use of electricity from low-carbon sources, such as electric kilns or induction heaters.

Carbonation hardening of Portland cement concrete is a promising method for reducing CO_2 emissions and improving the mechanical properties of the material. The combination of carbonation strengthening of Portland cement concrete with the use of nanomaterials and geopolymer materials contributes to the creation of more environmentally friendly, efficient and sustainable building materials. The addition of nanomaterials can improve the microstructure and mechanical properties of concrete, while geopolymer materials reduce the carbon footprint and increase strength. Ukrainian companies that manufacture building materials based on 3D printing technologies are a prime example of the successful implementation of this technology. Using xBeam 3D Metal Printing technology, complex metal parts can be created from industrial wire, and the method of jetting the binder opens up new opportunities for the production of high-precision ceramic products. Modern and environmentally friendly solutions for the construction materials industry in Ukraine include reducing the clinker ratio, using alternative fuels and raw materials, introducing green energy and improving the quality of cement through active mineral additives.

Steel recycling plays a key role in sustainable development, as it helps to avoid the negative environmental impacts associated with the production of steel from virgin raw materials. The use of recycled steel is more environmentally friendly than virgin steel, including the process of scrap sorting, melting in electric arc furnaces, adding alloying additives and forming end products, which allows secondary resources to be used efficiently and in an environmentally friendly manner. The use of circular economy, scrap sorting and carbon recovery are important strategies to ensure the efficiency and sustainability of steel processing in the context of climate change. Achieving climate neutrality targets requires a comprehensive approach and the involvement of all stakeholders in the building materials production process, including policymakers, builders, investors and architects, including the development of new technologies, the implementation of environmental policies and the promotion of green investments. Further research should be directed at improving 3D printing technologies and manufacturing new materials such as nanomaterials and geopolymers.

Conflict of Interests and ethics

The authors declare no conflict of interests. The authors also declare full adherence to all journal research ethics policies, namely involving the participation of human subjects anonymity and/ or consent to publish.

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