

Environmental Strategies and Future Trends in the Construction Chemicals Industry

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Abstract: Many production activities and operating systems have a significant negative impact regarding global warming, carbon footprint, and environmental effects. These are mainly due to extremely high production temperatures. In this regard, it is imperative to conduct a comprehensive analysis of the current situation and to act immediately. Reducing cement consumption, replacing cement with alternative binders with less CO₂ emission, substituting waste materials or bioresources instead of conventional raw materials, increasing the use of alternative fuels, boosting production efficiency, and integrating CO₂ capture systems into production play significant roles in structural energy management. The primary topics in operational energy management are thermal insulation, renewable energy sources, and water and waste management. Future trends are created by keeping up with the development of technology and adapting to the innovations in materials science. Therefore, emphasis must be placed on materials and their reactions, nanomaterials and their modifications, structural and functional materials, the development of high-quality materials, the comprehension of self-healing materials, energy applications, and fuel cells.

Keywords: Sustainable construction materials, Futuristic trends for construction sector, Structural energy, Operational energy

1. Introduction

The connection between human activity and climate change is undeniable. Observations indicate unequivocally that the climate is warming. The principal driver of the observed global warming during the past five decades may be attributed to the emissions of heat-trapping gases that are a direct result of human activities. Besides the combustion of fossil fuels such as coal, oil, and gas, the process of forest clearance, agricultural practices, and various other human activities also make substantial contributions to these emissions [1]. Regarding the life cycle usage of energy of urban constructions, operational energy (heating, cooling, ventilation, and hot water provision etc.) and structural energy (constructing, maintaining, renovating, and demolishing the constructed environment) can be distinguished [2]. Approximately 80% of the sum of all energy used by manmade structures is comprised of operating energy [1]. Operational energy analysis and its corresponding carbon emissions have served as guiding principles in the field of building energy research for an extended period. In recent years, there has been a growing emphasis on the significance of embodied energy and emissions. [3,4]. There are two reasons for this. It is expected that the proportion of operational energy and its corresponding carbon emissions would decline in the future as a result of the growing use of energy-efficient building technologies, advancements in insulating materials, and the usage of energy-efficient equipment and gadgets. [4,5]. Furthermore, it should be noted that emissions originating from the incorporation phase constitute a significant majority, surpassing 90%, of the whole life cycle emissions associated with "abandoned" built environments, including but not limited to roads, bridges, and various forms of infrastructure. [6,7].

Four air pollutants, namely SO₂, NO_x, CO, and CO₂, and particles PM_{2.5} (Less than 2.5 millimeter in diameter particulates), PM₁₀ (Less than 10 millimeter in diameter particulates), and TSP (utilised includes fragments) are emitted during cement production. Indirect emissions can also be attributed to the energy consumption involved in the manufacture and transportation of fundamental materials and end products. [8].

2. Sustainable Approaches for Structural Energy

Studies are carried out on different approaches to reduce emissions from cement. Approximately 7% of total CO₂ emissions are attributed to the cement manufacturing [9]. The predominant contributors to carbon dioxide (CO₂) emissions within the cement industry are the direct utilization of fossil fuels for burning purposes and the process of calcination, which involves converting limestone into calcium oxide. Indirect carbon dioxide (CO₂) emissions arise as a consequence of the burning of fossil fuels for the purpose of power generation. Roughly 50% of carbon dioxide (CO₂) emissions may be attributed

to the burning of fossil fuels, whereas the remaining 50% arises from the calcination process involving limestone. [10,11].

2.1. Optimization of Cement Production

Cement production component primarily consist of fly ash, blast furnace slags, pozzolan, and natural zeolites. Clinker consumption is reduced in cement production where these components are utilized [11].

2.2. Improving Aggregate Production

Coarse aggregates, following cement, constitute the principal contributor to carbon dioxide (CO₂) emissions within the context of concrete production, representing a range of 13 to 20% of the aggregate CO₂ emissions. The preponderance of CO₂ emissions in coarse aggregate production are attributed to blasting, excavation, and transport. The processes of grinding and sifting fine aggregates also contribute to the generated of CO₂ emissions. It has been determined that the emission additives produced by the concrete additives are relatively insignificant. Mixing, transporting, and placing concrete are known to contribute a negligible ratio of carbon dioxide to total concrete emissions [12,13].

2.3. Alternative Fuel Use in the Cement Industry

Cement production can utilize electricity derived from renewable energy sources. Additionally, in some countries, the heat produced by the combustion of refuse materials is utilized in production. The United States cement industry annually burns 53 million used tires. In 2005, approximately 200 kilotonnes (kt) of used tires, 450 kt of waste oil, 340 kt of sawdust, and 300 kt of waste plastic were burnt to produce cement in Japan [14].

2.4. Reducing the usage of cement

Recent developments have been made in the utilization of graphene, pozzolanic additives, and reactive silica in product design processes to reduce the use of cement. Graphene oxide is a viable candidate for use as a nano-reinforcement in cement-based materials due to its strong water dispersibility, high aspect ratio, and exceptional mechanical properties. There are studies to enhance the mechanical properties of Portland cement paste using graphene oxide. Adding 0.05% by weight graphene oxide can increase the graphene oxide-cement composite's compressive and flexural strengths from 15 to 33% and 41 to 59%, respectively [15,16].

It has been determined that micro and nano-sized pozzolanic additives can partially replace cement and increase the strength. It is known that particle size, fineness, and reactivity differences have the effect of accelerating the hydration reaction and slightly altering the reaction temperature. In the field of waste management, the use of pozzolans such as volcanic-derived pozzolans, fumed silica, and fly ash is also significant in terms of disposal convenience [17–19].

Various sustainable binders, such as calcium aluminate cements (CACs), super sulfated slag cements (SSCs), microbial cements (MCs), and geopolymer cements (GCs), can serve as viable substitutes for traditional Portland cement (PC). The use and acceptance of these alternative materials exhibit encouraging environmental efficacy, as they have the potential to reduce CO₂ emissions by 5-90%. This reduction in CO₂ release might potentially lead to a 7% decrease in world CO₂ emissions when compared to the fabrication of traditional cement [20,21].

2.5. Use of Natural and Recycled Fiber

The use of natural fibers and fibers obtained from waste materials instead of synthetic fibers is another approach for sustainability. There are published studies on the use of recycled plastic, metal, rubber, and glass fibers in the construction industry.

Plastic fibers are produced from a variety of synthetic polymers, including PET (polyethylene terephthalate), PE (polyethylene), PP (polypropylene), nylon, polyester, and other similar materials. Microfibres or macrofibres are categorized based on their size. The use of microfibers in concrete has been seen to decrease plastic shrinkage while compromising mechanical and tensile characteristics. On the other hand, macrofibres provide an added advantage by mitigating the occurrence of drying shrinkage and improving the responsiveness after cracking. [22,23].

Steel fibers, which are readily accessible in a range of forms and diameters, are employed either alone or in conjunction with rubber or polymers. The use of steel fibers enhances the ductility and resilience of concrete to fatigue, impact, explosion, and abrasion. In addition, cracks are constrained in terms of their breadth. [22].

Rubber particles in the form of powder, crumbs, or fibers have the potential to be included into concrete mixtures, resulting in the development of rubberized concretes. These rubbers are always obtained from a recycled origin, commonly sourced from used tires. Rubber provides high ductility and durability to concrete. The limited compressive strength of cement and rubber materials can be attributed to the relatively weak connection between their particles. To meet the criteria of shock resistance, particularly in seismic occurrences, and to provide sound insulation, this material is

predominantly employed in non-load-bearing constructions such as highways, lightweight concrete walls, building facades, roofing tiles, and road traffic barriers [24,25].

Glass fibers, which are typically added in high doses, are frequently used in reinforced materials that provide desirable attributes such as hardness or ornamental value. However, the utilization of glass in construction materials has been restricted as a result of its susceptibility to alkaline environments created by cement, which causes it to become brittle and reduce its strength and durability. With the development of glass fibers that are resistant to alkalis, the use of glass fiber in construction is on the rise. The majority of recycled fibers from glass for reinforced concrete are derived from refuse polymers strengthened with glass fibers [26].

Natural fibers are naturally occurring, biodegradable, and safe to consume, and their mechanical properties are more desirable than those of synthetic fibers. Their hydrophilic character, however, renders them vulnerable to high-volume transpiration of moisture, resulting in insufficient matrix wetting and a compromised fiber-matrix interface. Adapting the interface properties and enhancing the durability and mechanical behavior of cement and geopolymer-based composites requires adaptation and functionalization strategies for natural fibers. Recently, cellulose, hemicellulose, lignin, pectin, oils, lubricants, lipids, and fibers derived from animals have been utilized in the construction industry as natural fiber materials [27].

2.6. Replacing traditional raw materials with sustainable or waste materials

There are efforts to replace the conventional production's raw materials with more environmentally favorable alternatives. Numerous academic studies have been conducted, and the construction sector is beginning to observe their effects. Construction debris can be used in concrete, asphalt, and composite materials [28,29]. While some countries make this approach legally compulsory, some countries encourage it without any legal obligation. In the US, Executive Order 13101, "Greening the Government Through Waste Prevention, Recycling and Federal Acquisition," prioritized biobased materials and increased federal government purchases to 50% over the next few decades. This rule covers construction materials, composites, adhesives for the housing industry, fiber, paper, and packaging, plastics, paints, and coatings [28]. Figure 1 presents the suggested minimum biobased content for certain items under the Construction Material Category.

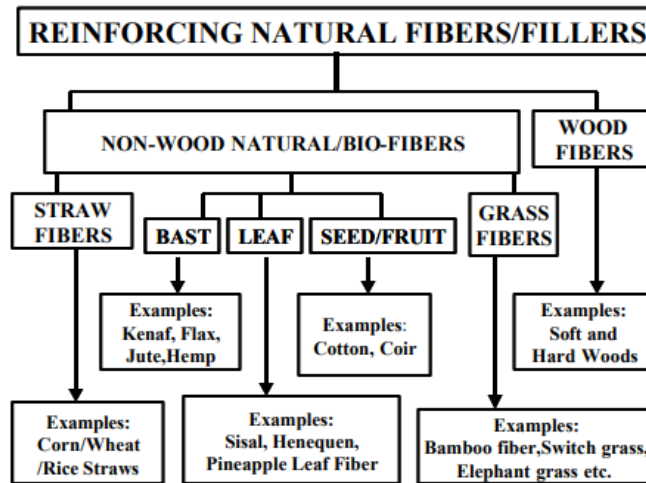


Figure 1. Natural/Bio-fibers for Bio composites for the Housing Industry in USA [28]

In addition to the evaluation of waste materials, there are also studies in which some chemically synthesized raw materials are substituted with biobased alternatives [30]. Although this approach is uncommon in the business world, it is anticipated to become more popular in the future.

2.7. Max yield/ low energy consuming production

Despite the fact that the construction industry lies behind sectors such as aviation and automotive in adapting to evolving technology, it is also possible to observe that there is a perception towards adapting to today's technology. Adaptation of Internet of Things (IoT) technology to the construction industry is a prime example. Possible IoT applications include monitoring cement hydration, filling size, increasing production efficiency, surveillance of structural health, safety in the construction industry enhancement, optimization and simulation, image processing and monitoring certain pre-test requirements [31–35].

The precise measurement of the compressive strength in its original location has the potential to enhance critical construction procedures, including the timing for removing formwork, opening bridges, tensioning prestressed cables, and designing concrete mixes. The optimization of mix design has a significant impact on the efficient exploitation of raw resources, including cementitious materials and aggregates, as well as replacement components such chemical admixtures. The use of such a strategy has the possibility to yield significant financial advantages by mitigating CO₂ emissions, reducing labor and project expenses, and expediting project completion within the designated timeline [32].

In addition to the IoT, cloud computing and Industry 4.0 Technologies are used to increase production efficiency and provide energy savings [36,37].

2.8. CO₂ Capturing

Excessive CO₂ emissions into the atmosphere are identified as one of the primary causes of climate change and global warming [38,39]. For the upcoming years, decisions have been made to better living conditions and reduce CO₂ emissions, the primary CO₂ sources have been identified, and precautions have been taken regarding these sources. Technology for CO₂ capture, storage, and utilization is a promising option for achieving significant reductions in anthropogenic CO₂ emissions [40,41]. Important classes of solid materials have been evaluated as adsorbents for this purpose, including metal-organic frameworks (MOFs), silica-based materials, calcium-based materials, zeolite and carbon-based materials. Carbon-based materials such as activated carbon, mesoporous carbon (CMK), carbon nanotubes, and graphene oxide are widely employed as solid adsorbents. [42–51].

3. Sustainable Approaches for Operational Energy Consumption

In terms of Operational Energy, it is possible to implement measures during both the design and operate phases.

3.1. Design phase approaches

The design of buildings is optimized to take advantage of sunlight with maximum efficiency and to prevent heat loss caused by glass. During the architectural design process of a building, studies are conducted to determine the optimal glass width and distribution, with calculations taking into consideration the time and angle of the sun's position. The window-to-wall ratio is a crucial metric that, when properly constructed, may exert a substantial impact on the overall energy consumption of a structure. Numerous studies have been conducted to assess the effects of solar radiation and sunlight penetration into a structure via its exterior [52–54].

The implementation of thermal insulation in building walls has a notable influence on reduction of thermal energy consumption within structures, which leads to a decrease in CO₂ emissions. The implementation of thermal insulation on the outer wall of a building can be regarded as a prudent economic investment. The cost of this investment encompasses the expenses is related to the purchase, transportation, and installation of the insulation, whereas the return is contingent upon the decrease in thermal energy consumption [55]. In the literature are also included studies involving construction scenarios that reduce operational carbon by enhancing thermal coating. There are numerous methods and programs for simultaneously estimating embodied and operational carbon over the lifetime of thermal coating categories for buildings [56]. Thermal coating can be applied during the construction phase of the building as well as it's service time.

3.2. Usage phase approaches

Within the context of European research projects, a novel lifecycle methodology has been devised to assess the lifecycle impacts of buildings at the earliest phases of design. The approach that has been suggested involves estimating the operational energy requirements of the building. Early design stages are anticipated to have a greater impact on the life cycle performance of the building, despite the limited availability of design data at these stages. In addition, the estimation of energy requirements is frequently based on a practice-based method that necessitates a comprehensive description of the building's design [57].

Energy performance may be categorized into three main components: operational energy, active structures that make use of renewable energy sources, and the handling of energy operation and management. Operational energy is the combination of energy elements such as energy use for heating, domestic hot water, air conditioning units, cooling, lighting, and appliances. Renewable energy-based active systems encompass a range of technologies, including water heaters powered by solar energy, heating and cooling pumps, photovoltaic systems, and heat recuperation mechanisms. The concept of energy operation and management encompasses the comprehensive regulation of lighting systems, occupancy sensors, and technological control of appliances. [58,59]. In this context, the management of water is another issue that can be evaluated. There are various approaches to water management, including reducing and modulating water flow, surface water hydrology, provision of safe drinking water, and filtration of wastewater. Waste Management, on the other hand, involves minimizing the residues generated by building operations. This study examines strategies for mitigating emissions arising from the construction, operation, and destruction of the structure, alongside steps aimed at decreasing the potential hazards associated with the facility's operation [59].

The achievement of sustainable energy performance through the utilization of combined technologies and green energy systems continue to face significant obstacles in terms of crucial parameters such as cost, maintenance, and operation. Future eco-cities must be designed by designers, engineers, and creators in concert with the goal of creating greener and more intelligent environments [60].

4. Conclusion

Taking into account all effects, such as energy consumption, carbon emissions, water footprint, and public and environmental health, it is evident that the current global situation must be improved immediately. All of the titles enumerated in the preceding section depict current and immediate developments. In light of these factors, the following subjects should be prioritized:

- Understanding nanoscale phenomena (such as cement hydration)
- Nano particulates, additives and admixtures
- Materials with nanostructure modifications (e.g., steel, cement, composites)
- New structural and functional materials
- Engineering surface/interface assessment
- Specialized paints, varnishes, and thin films
- Integrated monitoring and diagnostic systems for structures
- Self-healing and intelligent materials
- Innovative thermal and insulating materials
- Intelligent construction equipments, command and control systems
- New fuel cells and solar cells for building energy applications
- Biomimetic and hybrid materials

Given that environmental changes manifest on a worldwide basis, it is imperative that recovery measures be implemented on a global scale as well. The most optimal approach to address improvement requirements globally is through the implementation of rules and legislation, ensuring the promotion of health and well-being.

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