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 crucial to conduct a thorough analysis of the current situation and act immediately. Reducing cement consumption, replacing cement with alternative binders with less CO_2 emission, substituting waste materials or bioresources instead of conventional raw materials, increasing the use of alternative fuels, boosting production efficiency, and integrating CO_2 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. Human-induced emissions of heat-trapping gases are the primary cause of the observed global warming over the last 50 years. In addition to the combustion of fossil fuels (coal, oil, and gas), forest clearance, agricultural practices, and other manmade activities effect significantly to these emissions [1]. In terms of the life cycle energy consumption of the urban buildings, operational energy (heating/cooling, ventilation, hot water, etc.) and structural energy (construction, maintenance, renovation, and demolition of the built environment) can be distinguished [2]. Approximately 80% of the total energy consumption in the built environment is comprised of operating energy [1]. However the analysis of operational energy and its associated carbon emissions has dominated building energy research for many years. Recently, the significance of embodied energy and emissions has become apparent [3,4]. There are two reasons for this. First, the proportion of operational energy and its associated carbon emissions are anticipated to decrease in the future due to the increased use of energy-efficient building technologies, more advanced and effective insulation materials, and energy-efficient apparatus and devices [4,5]. Second, incorporated emissions account for more than 90% of life cycle emissions for 'abandoned' built environments such as roads, bridges, and other infrastructure [6,7].

Four air pollutants, namely SO_2, NO_X, CO, and CO_2, and particles PM2.5 (particles with a diameter of less than 2.5 mm), PM10 (particles with a diameter of less than 10 mm), and TSP (total used contains particles) are emitted during cement production. Indirect emissions also result from the consumption of energy during production and the transportation of basic materials and finished goods [8].

2. Sustainable Approaches for Structural Energy

Studies are carried out on different approaches to reduce emissions from cement. Approximately 7% of total global CO_2 emissions are attributed to the cement industry [9]. The primary sources of CO_2 emissions in the cement industry are the direct combustion of fossil fuels and the calcination of limestone to calcium oxide. Indirect CO_2 emissions result from the combustion of fossil fuels to produce electricity. Approximately half of the CO_2 emissions are caused by the combustion of fossil fuels and the other half by the calcination of limestone [10,11].

2.1. Optimization of Cement Production

Cement production component primarily consist of fly ash from coal-fired thermal power plants, blast furnace slags from the iron and steel industry, pozzolan, and natural zeolites. Clinker consumption is reduced in cement production where these components are utilized [11].

2.2. Improving Aggregate Production

After cement, coarse aggregates are the primary source of CO_2 emissions in concrete, accounting for 13 to 20% of total CO_2 emissions. The preponderance of CO_2 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 CO_2 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 waste 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 increases 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].

As an alternative to conventional Portland cement (PC), calcium aluminate cements (CACs), super sulfated slag cements (SSCs), microbial cements (MCs), and geopolymer cements (GCs) are varieties of sustainable binders. The production and adoption of these alternative materials demonstrate promising environmental performance: a 5–90% reduction in CO_2 release could contribute to up to a 7% reduction in global CO_2 emissions compared to PC manufacturing [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 derived from numerous synthetic polymers, such as PET (polyethylene terephthalate), PE (polyethylene), PP (polypropylene), nylon, polyester, and others. Based on their size, they are classified as microfibres or macrofibres. The incorporation of microfibers into concrete tends to reduce plastic contraction at the expense of mechanical and tensile properties. In contrast, macrofibres offer the additional benefit of preventing drying shrinkage and enhancing post-cracking response [22,23].

Steel fibers, which are commercially available in various shapes and sizes, are used alone or in combination with rubber or polymers. Concrete's ductility and resistance to fatigue, impact, explosion, and abrasion are enhanced by steel fibers. They also limit the width of cracks [22].

Rubbers in the form of powder, crumbs, or fibers can be added to concrete to create so-called rubberized concretes. These rubbers are always obtained from a recycled source, typically discarded tires. Rubber provides high ductility and durability to concrete. Due to the weak bond between cement and rubber particles, the compressive strength of these materials is minimal. In order to satisfy the requirements of shock resistance, for example during seismic events, and sound insulation, it is primarily used for roadways in non-load-bearing structures, in 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 where hardness or decorative value is desired. However, the use of glass in building materials has been limited due to its sensitivity to alkaline conditions provided 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 glass fibers for reinforced concrete are derived from refuse polymers reinforced with glass fibers [26].

Natural fibers are renewable, biodegradable, and non-toxic, and their mechanical properties are more desirable than those of synthetic fibers. However, their hydrophilic nature makes them susceptible to high-volume moisture absorption, resulting in inadequate matrix wetting and a weakened fiber-matrix interface. In order to adapt the interface properties and improve the durability and mechanical behavior of cement and geopolymer-based composites, modification and functionalization strategies for natural fibers are crucially essential. 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]. The minimum biobased content proposed for some of the items in the Construction Material Category are tabulated in Figure 1.

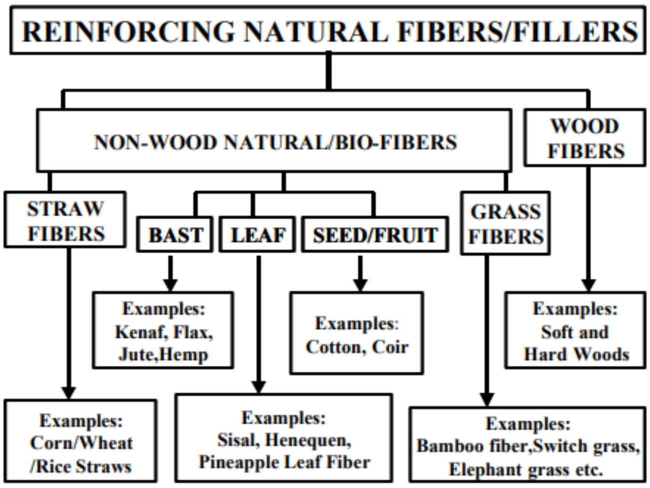

Figure 1. Natural/Bio-fibers for Bio composites for the Housing Industry in USA [28]

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, structural health monitoring, construction safety, optimization and simulation, image processing and monitoring certain pre-test requirements [31–35].

An accurate in-situ estimation of the compressive strength provides the opportunity to optimize crucial construction operations, such as formwork removal time, bridge opening time, prestressed cable tensioning time, and mix design. The optimization of mix design influences the utilization of raw materials (such as cementitious materials and aggregates) and substitute materials (such as chemical admixtures). This could reduce CO_2 emissions, labor and project costs, as well as project deadline, resulting in a significant financial benefit [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. CO_2 Capturing

Excessive CO_2 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 CO_2 emissions, the primary CO_2 sources have been identified, and precautions have been taken regarding these sources. Technology for CO_2 capture, storage, and utilization is a promising option for achieving significant reductions in anthropogenic CO_2 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. Activated carbon, mesoporous carbon (CMK), carbon nanotubes and graphene oxide are extensively used as solid adsorbents among carbon-class materials [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 design phase 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 possition. The window-to-wall ratio is one of the important parameters and, if designed correctly, can have a significant effect on the building's overall energy consumption. There are studies conducted to determine the impact of solar radiation and daylight penetrating a building through its envelope [52–54].

Thermal insulation of building walls has a significant impact on reducing thermal energy consumption in buildings, which leads to a decrease in CO_2 emissions. Having thermal insulation on the exterior wall of a building can be viewed as an economic investment. In this investment, the cost is related to the purchase, transportation, and installation of the insulation, while the profit is linked to the reduction of 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 approches

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 proposed method 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 can be divided into operational energy, active systems utilizing renewable energy sources, and energy management operation and management. Operational energy is the combination of energy elements such as heating energy consumption, domestic hot water energy consumption, air conditioning unit energy consumption, cooling energy consumption, lighting energy consumption, and appliance energy consumption. Active systems utilizing renewable energy sources consist of solar water heaters, heat pumps, photovoltaic technology, and heat recuperation. Operation and management of energy can be defined as sum of control of lighting systems; occupancy sensors and technical 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 flow, potable water supply, and filtration of wastewater. Waste Management, on the other hand, involves minimizing the residues generated by building operations. This scope evaluates measures to minimize emissions resulting from the construction, operation, and demolition of the building, as well as measures to reduce the risk of hazardous material resulting from the operation of the facility [59].

Sustainable energy performances associated with integrated technologies and renewable 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 architects, engineers, and developers 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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