Waste Management for Green Concrete Solutions

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Reinforced concrete based on ordinary Portland cement (OPC) is one of the most commonly used materials in modern buildings. Due to the global growth of the building industry, concrete components have been partially or completely replaced with waste materials that can be used as binders or aggregates.

Keywords: green concrete ; waste management ; waste as a cement filler

1. Introduction

Constant technological progress and increasing expectations of the market determine the growing demand for modern technologies and products used in everyday life. Many of the technologies known and used for years are based on the linear economy model: take–make–dispose [1]. Nevertheless, the depletion of natural resources of many types of raw materials, the deteriorating quality of the environment, issues with the management of increasing amounts of waste, and thus the environmental and climatic changes taking place currently as a result of pollution have contributed to a shift in the public awareness and have significantly influenced economic models and legal regulations. The past few years have brought changes in the industry that have led to a trend of replacing the classic linear economy models in material manufacturing to a closed circular economy model. The circular economy model is constantly being introduced in various industrial sectors, and one of its main assumptions is the reuse of raw materials contained in waste. This concept can be applied widely to manufacturing processes of concrete with reused additives, resulting in materials with altered properties.

1.1. The Composition of the Ordinary Portland Cement

Due to the constantly increasing world population and economic growth, one of the most developing industries is the building sector, in which a wide variety of novel materials are used. Despite many technological innovations in the building industry, cement remains the main concrete component, acting as a strong binding agent or adhesive material strengthening constructions. Concrete includes mainly ingredients such as an ordinary Portland cement (OPC), based on tricalcium silicate ($3CaO{\cdot}SiO_2$), dicalcium silicate ($2CaO{\cdot}SiO_2$), tricalcium aluminate ($3CaO{\cdot}Al_2O_3$), and a tetra-calcium aluminoferrite ($4CaO{\cdot}Al_2O_3Fe_2O_3$) made by heating limestone and clay up to 1400 °C. The most commonly used OPC is calcium–silicate–hydrate (C–S–H) hydraulic cement [2]. The cement market is booming and the global cement market will grow from USD 326.80 billion in 2021 to USD 458.64 billion in 2028, with a compound annual growth rate (CAGR) of 5.1% in the 2021–2028 forecast period, while the global green cement market will record an increase of 14.1% CAGR in 2017–2023. The driving force behind the global green cement market is, among others, the growing awareness of the reduction in carbon dioxide emissions and their harmful impact on the environment. Moreover, the building industry, to meet the requirements of Leadership in Energy and Environmental Design (LEED), focuses on green construction [3][4]. Additionally, a new sustainability index for mortars and concrete as a modification of the Empathetic Added Sustainability Index (EASI) was proposed [5].

1.2. Environmental Hazards

Production of the main ingredient of cement, i.e., OPC, contributes to tremendous air pollution, as it is a source of noxious gasses emissions such as carbon dioxide. In fact, the OPC manufacturing process covers about 8% of the world’s human carbon dioxide emissions [6][7], while depending on the type of cement and the production process used, each ton of OPC produced requires 60–130 kg of heating oil or other substance and approximately 110 kWh of electricity [8]. Since climate change occurs because of the release of greenhouse gasses into the environment, the building industry began to implement a carbon-retaining production process. This has resulted in the manufacturers applying recycled ingredients, low-emission fuels, or the combination of low-carbon content materials, which have a cement property with clinker [9]. The price of cement is rising because of both depletion of natural resources and an increase in the environmental taxes [10].

1.3. Modification Methods

The development of improved production methods and concrete composition to ensure the reduction or elimination of CO_2 is highly important. In recent years, this has increased the need for changes in concrete and its components' manufacturing, particularly waste additives. Green concrete consists of a binder made from supplementary cementitious materials (SCMs), in which the OPC has been partially or entirely replaced with another material and/or waste and recycled materials as aggregates [11]. The materials of waste origin used in fresh concrete can be divided into three main groups: industrial, agricultural, and municipal waste. To improve concrete properties like workability, structure, and later-age strength properties, the waste material in concrete is often activated by physical, chemical, or physicochemical processes. The first one is breaking down the ingredients into smaller particles, which increases their effective surface area. The second one, the most efficient and widely used type of activation, is the use of a chemical substance, which activates the pozzolanicity of cement's ingredients. Concrete is chemically activated with the help of substances such as sodium sulfate anhydrite, sodium silicate, acid, or calcium formate [12]. In turn, both activation methods are combined to reduce or even remove inconsistencies in their chemical properties [13]. Because of this, depending on the additives within the concrete, the physical properties of the concrete can be improved.

Researchers discuss the recent solutions in applying waste materials as ingredients of the concrete that are treated as green additives and compare them with the typical solutions used in concrete. Waste-based additives offer a sustainable stream to the future demand for concrete preparation, enhancing concrete's mechanical properties, lowering the production costs, and opening up sustainable avenues for waste management. Researchers present different concrete additives, with their varying mechanical properties, and discuss their advantages and disadvantages, including the economic and environmental aspects. **Figure 1** presents the most common additives in the preparation of the green concrete that are mentioned.

Figure 1. Schematic diagram presenting the variety of cement additives to prepare green concrete.

2. Green Additives to Concrete

Based on the review of selected literature sources, the main types of green additives used in the production of concrete were determined. The summary being an introduction to the green additives section is presented in **Table 1**.

Green Additive	Application	Influence on Properties of Concrete
Slag [14][15]	Binder component	Improvement in mechanical and strength properties
Wheat straw ash [16][17][18]	Binder component	Reduction in the spontaneous shrinkage of high-performance concrete and the final autogenous contraction of concrete
Alkali-activated materials [19]	Binder component	More favorable properties of the entire concrete, such as low thermal conductivity, high volume stability, rapid strength gaining, fire, and chemical erosion resistance
Calcium aluminate and calcium sulphoaluminate (mineral wool waste) [20][21][22]	Binder component	Improvement of sulfate resistance, enhancement of mechanical properties, increase in compressive strength
Waste glass powder [23][24]	Sand substitute	Improvement of concrete mechanical properties, such as concrete tensile strength, compressive strength, and porosity

Green Additive	Application	Influence on Properties of Concrete
Marble mud dust [25]	Sand substitute	Improvement of the strength of concrete, freezing properties and resistance to thawing and peeling of the concrete surface
Aggregates from the recycling of construction and demolition waste [26][27][28][29][30][31]	Component of concrete materials	Improvement of the concrete, especially those used in lower-level applications
Tire rubber-based additives [22][26][32][33][34][35][36][37]	Gravel substitute, composite filler, additive to sand mortar	Reduction in the concrete's weight, improvement of the compressive and flexural strength, reduction in compression and tension and a reduction in Young's modulus of elasticity, reduction in thermal conductivity
Plastic fibers [38][39]	Concrete filler	Improvement of compression performance, durability, flexural and tensile strength, reduction in the weight of concrete possible release of plasticizers, flame retardants, pigments and heavy metals to the environment
E-waste [40][41][42][43][44][45][46][47]	Concrete filler	Improvement of the comprehensive strength of the concrete, tensile, flexural and shear strength, and durability properties, possible release of many harmful compounds to the environment
Biochar		
Rice husk [13][48][49][50][51][52]	Cement binder	Reduction in compressive strength, increase in the permeability of the concrete
Bamboo waste [53][54]	Pozzolanic material	Improvement of mechanical properties, resistance to cracks
Rice straw [52]	Cement binder	Improvement of the compressive and tensile strengths, and thermal conductivity
Food and wood waste [55]	Mortar component	Increase in the compressive strength, sorptivity, resistance to water penetration, and ductility compared to conventional mortar
Forest wood chips [55]	Cement binder	Improvement of the fracture energy, slight decrease of the flexural strength
Agricultural waste		
Wild vegetal plant [56]	Fibrous reinforcing additive	Improvement of the mechanical strength, positioning of fibers horizontally enhances adhesion with the cement paste
Waste products obtained in palm oil and coconut oil processing [57][58][59][60][61]	Gravel substitutes	Reduction in concrete production costs, improvement the mechanical properties of the mortar, such tensile strength, with the decrease of the compressive strength of concrete
Hemp fibers [62][63][64]	Mortar component	Improvement of the thermal stability of mortar and compressive strength
Nanocellulose Fibers [65]	Composite material	Improvement of the mechanical strength, microstructure, the ductility and hardness of concrete
Vegetal fibers (i.a., prickly pear fibers, pinpeare needle fibers, banana fibers) [66][67][68]	Concrete composites	Reduction in the compressive strength, improvement in the flexural and the splitting tensile strength of the concrete, change in thermal properties such as lower thermal conductivity and specific heat capacity, and high thermal diffusivity

As a concrete substitute, high-quality supplementary cementitious material, composed of waste from other industries, constitutes waste management and can also be applied. The amount of traditional SCMs such as fly ash and slag is limited, particularly in underdeveloped countries. Other materials to partially replace ordinary Portland cement are of high importance. For example, calcium aluminate concentrate products from the recycling of sanitary waste improve mechanical properties and the high-temperature behavior of Portland cement [22]. CAC provides a practical possibility of recycling glass waste in the production of building materials. Moreover, CAC is also a promising additive to Portland cement to produce 3D-printing mixtures, which are characterized by very good mechanical properties. Other widely available waste materials that can be used as components of green cement are sugarcane bagasse ash (SCBA) [69], geopolymer metakaolin (MK), and millet husk ash [18]. These compounds provide higher compressive strength and split tensile strength than conventional concrete. Factors such as the presence of uncalcined kaolinitic clay or swelling clays affect the fresh and hardened properties of the concrete [70]. Other alternative binders in concrete provide the alkali-activated binders, which require a significant amount of energy and generate a considerable amount of carbon dioxide during the production process.

Since the literature widely describes the application of many waste materials from demolition waste, glass waste, plastic fibers, carbon black from spent tires, alkali-activated binders, biomass-derived biomass, and non-carbonized plant-based materials, primarily the mechanical strength of the modified concrete is described [27][28][29][30]. So far, focus has been placed mainly on the mechanical properties of green concrete.

Agricultural waste shows excellent potential in the building industry, particularly in areas with high agricultural production, which results in enormous environmental liabilities in some countries. It can improve the mechanical strength, working performance, and durability of concrete, as these parameters depend on the number of materials incorporated in cement. Both agricultural waste and biochar particle application as a concrete filler reduce waste accumulation and prevent natural resource depletion, reducing environmental pollution caused by carbon dioxide emissions. However, these materials can be at different maturity levels and derived from various regions, so their physicochemical properties may vary, influencing the concrete's properties. For that reason, natural biomass sources require pretreatment methods to improve the mechanical properties and durability of green biomass-based waste concrete. At the same time, the mechanical, compressive, and flexural strength along with the stability of the non-carbonized waste-based concrete needs improvement to increase the loads of the concrete; however, the addition of natural crops or fibers is a lightweight solution. Pyrolyzed biomass acts well as a gravel substitute, making it a promising aggregate, especially for its small size and usually alkali pH that improves the stability of the concrete. That feature enhances the corrosion resistance, especially in steel-reinforced concrete, where the alkali media can delay the corrosion. Hence, the application of the carbon-based particles in the concrete seems to be the most promising solution for the wide availability of biomass waste, physicochemical properties, and low production costs. In turn, concrete containing biochar has a lower density than conventional concrete, and consequently, its scope of application is greater. In addition, the compressive strength, flexural strength, and splitting tensile strength in the case of biochar-based concrete present a substantial increase. Another interesting alternative is the usage of marine brown algae as a natural polymer in concrete [71].

The e-waste can be used as a concrete additive; however, its use requires adequate safety procedures. E-waste contains many harmful chemicals from heavy metals such as lead, cadmium, and mercury, and many organic compounds that can be easily released into the soil, water, and air. The concrete-filled e-waste is still called green as an effective way to manage the spent electronic materials; however, from the ecological point of view, that type of concrete is far from the "green" approach and requires much more materials and energy consumption than the other concrete additives. Moreover, the e-waste addition to concrete seems controversial and non-ecological, and may generate severe health problems if the harmful materials were to leak under the concrete operation because of exposure to environmental elements.

Another important environmental issue is connected with the high level of freshwater consumption during the manufacturing process of the concrete, in particular in the countries in which the supply of fresh water is limited. Freshwater, a hydration reagent and the ion transport medium, can be replaced with recycled water from wastewater. Therefore, wastewater can be used for the concrete preparation, reducing production costs. However, as water is a good solvent, it would need pretreatment depending on the wastewater source to avoid releasing chemicals that would be harmful to the environment and health. Besides the many concrete applications, steel-reinforced concrete is one of the most widely used materials in the building industry, and each additive can affect the corrosion of the reinforcement. The application of waste materials also needs to be tested on reinforced concrete. Green concrete offers many advantages, such as reducing concrete production time, shortening the waiting time for curing, lowering construction costs, and, consequently, earlier construction project completion. Still, building regulations, including such data as the levels of clinker and chemical concrete, the cement's composition, or insufficient data on the long-term durability of the structure, and the selection of green concrete depending on its application, are the main challenges in the use of green concrete. The critical issue is also the development of new and affordable activators.

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