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Green concrete: A review of recent developments

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ABSTRACT

So much innovations have ensued in the concrete industry in the last decade, especially in terms of ensuring concrete sustainability and its green initiatives. A call for sustainability is imminent in the industry as the production of ordinary Portland cement (OPC) which is the main binder of concrete contributes about 8% to the world's human-induced carbon dioxide emission. In addition, the production of concrete has posed a huge threat on natural deposits of raw materials. With billions of tons of concrete expected to be produced in the coming years to meet our infrastructure demand, it is critical for other alternatives to be considered for concrete production. Such alternatives mostly fit as partial or total replacement of OPC and aggregates. This paper explored the sustainable advantage of alkali-activated binders, supplementary cementitious materials, and recycled materials as raw materials in concrete. This short review has shown that it is possible to achieve a greener concrete with enhanced properties compared to the conventional concrete with the use of new materials. Also, on the ground of economic importance, the new materials were found to have better performance than the conventional ones.

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1. Introduction

Concrete is more sustainable in terms of energy consumed, and carbon emission per volume compared to other building materials such as steel [1] as shown in Fig. 1. However, the high-volume consumption of concrete compared to other building materials have eliminated this sustainable advantage. The production of ordinary Portland cement (OPC) which is the main binder in concrete contributes about 8% to the world's anthropogenic carbon emission and uses about 3% of the world's energy [2]. Also, the concrete industry is the highest consumer of natural aggregate and fresh water [3,4]. The higher production of concrete for future usage will lead to significant depletion of these natural resources and contamination of the environment [5,6]. Therefore, the need to have green concrete is essential so as to meet future demands of concrete while conserving natural resources. Green concrete can be classified as any concrete that has less embodied energy and carbon compared to the conventional OPC concrete. In addition, green concrete essentially incorporates different waste materials as either binder or/and aggregate.

Therefore green concrete can be in various types; such as concrete with partial to total replacement of OPC as a binder, or/and concrete incorporating waste and recycled materials as aggregate [8]. Apart from sustainability issues, the necessity to have concrete that is strong and durable has propelled the development of green concrete that can resist load and various detrimental forces in the environment. The prospects of green concrete to produce excellent fresh and hardened properties compared to the conventional OPC concrete will ensure low maintenance cost, quick completion of constructions, and extended service life. Though the author presented the current sustainability issues associated with the concrete industry in an article not yet published [9], this present article explored the major developments that are being used to achieve a green concrete. The use of different alternative components to produce green concrete are discussed along with their resulting effects on the properties of the green concrete. It is hoped that this article will serve as a guide for stakeholders in the construction industry looking to improve the sustainability of concrete. It is also anticipated this paper will create an avenue for

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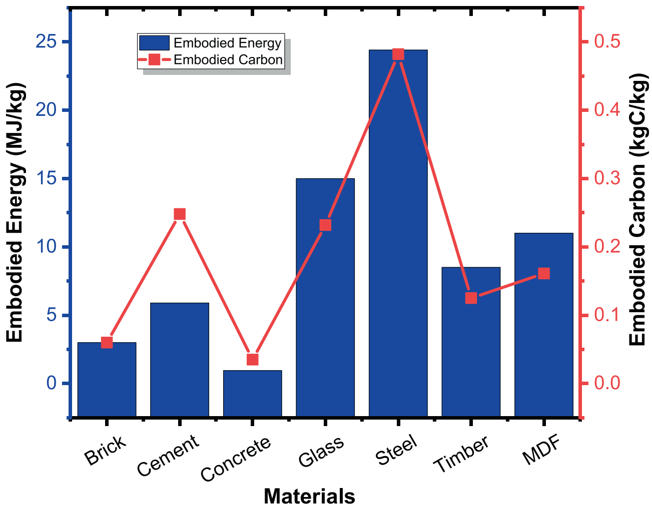

Fig. 1. Embodied energy and carbon for building materials (data from [7]).

further improvement and optimization of current green initiatives and will foster the development of new ones.

2. Recent developments

As earlier stated, green concrete is capable of sustaining the ecosystem while reducing the overall cost of concrete. Several developments towards green concrete have ensued and this varies from partial to total replacement of different components in concrete with alternative sustainable materials. These initiatives have been used individually or combined with other green initiatives. The major recent developments noted within the last few decades are further explained and categorized.

2.1. Supplementary cementitious as partial replacement of OPC

As the production of OPC is the major energy consumer and contributor of carbon dioxide emission in concrete, its partial replacement with alternative material with less embodied energy and carbon will result in significant reduction in overall embodied carbon of concrete. Supplementary cementitious materials (SCMs) are green alternatives to partially replace OPC as a binder in concrete. SCMs possess both pozzolanic and filler properties which embodied it with the capabilities to enhance both the mechanical and durability properties of concrete. SCMs serves as a green alternative because they are mostly waste products from other industries, and their use in concrete creates an avenue to manage these waste effectively. In addition, their use in concrete results in conservation of several land spaces and natural deposits of raw materials that could have been used for their disposal, and mining raw material for OPC production respectively.

SCM can be used to replace OPC in concrete in the range of 10–50% [10]. However, this range can be increased depending on the desired properties. Generally, SCMs improve the properties of concrete by their pozzolanic and filler properties. Silica fume (SF) which is a byproduct of ferrosilicon production has been used over the decades as SCM in concrete. The partial replacement of OPC with SF has been shown to not only reduce the overall carbon dioxide emission of the concrete, but it also enhanced its mechanical properties [11]. Also, Rice husk ash (RHA) which is an agricultural waste and a type of SCM has been reported to enhance the early strength and durability of concrete [12]. The improved properties of concrete with the use of RHA as partial replacement of OPC has been attributed to the refinement of the microstructure and densification of the interfacial transition zone (ITZ) between the aggregate and paste [12–14]. However, it should be noted that the incorporation of RHA into concrete leads to detrimental effects on the fresh properties of the concrete. Increase in water requirement and a decrease in flowability are the main negative effects observed when RHA is used as partial replacement of OPC in concrete. In addition, past certain replacement levels, impaired mechanical and durability properties such as a decrease in compressive strength and increase in permeability can ensue. Therefore, initial small-scale testing and proper optimization are essential before RHA is incorporated as partial replacement of OPC in concrete on a large scale. The optimum replacement level required varied between studies as the properties of RHA is affected by various parameter such as location, combustion condition, type of fertilizer used, etc. Therefore, to use any SCMs as partial replacement of OPC in concrete, it is essential to do initial tests to determine the optimum replacement level. Use of fly ash (FA) from coal burning in power generation as SCM has also been reported to improve the properties of concrete [15,16]. However, in order to achieve the maximum benefits such as enhanced properties, proper replacement level and curing methods have to be employed [17,18]. When FA is used at high replacement level of OPC, detrimental effect such as a slow rate of strength development, longer set times and lower early age strength can be evident. In addition, durability issues such as scaling carbonation, alkali-silica reactions can result from high volume use of FA as partial replacement of OPC [19].

Slag (SL) is also one of the common SCMs used as partial replacement of OPC in concrete. Slag is obtained as a waste product from the metal industry and has been reported to improve both the mechanical and durability properties of concrete [20,21]. Chidiac and Panesar [22] suggested a ratio of 1:4 for SL to OPC, at 0.30 water to cementitious ratio as optimum. Lower ratio of SL to OPC is encouraged as higher replacement levels might lead to shrinkage and bleeding [23,24]. In general, with improved properties and reduction in the overall embodied energy and carbon of concrete with the use of SCMs as partial replacement of OPC, higher replacement levels lead to detrimental effects on both the fresh and hardened properties. For example, an increase in replacement level of OPC with SCMs lead to decrease in the slump. Reduction in the slump with increasing SCMs levels has been attributed to their high water absorption capacity and specific surface area [25]. It should, however, be noted that each SCM as its own optimum water to cementitious ratio and replacement level. Therefore, proper small-scale studies have to be done to determine these optimum values, as the reactivity of SCMs vary even for the same type of SCM [26].

2.2. Alkali-activated binders

Alkali-activated binders (AAB) are one of the main promising green alternatives to conventional OPC. This is as a result of the total elimination of OPC with aluminosilicate precursors which are mostly waste product from different industrial processes. Total elimination of OPC from concrete means a remarkable improvement in the sustainability of concrete. Carbon dioxide emission reduction up to 80% have been reported in the literature when AABs are used in place of OPC [27]. The use of these aluminosilicate precursors in concrete also creates an avenue to manage the waste effectively. Common aluminosilicate precursors are fly ash from power generation industry, slag from iron industry, rice husk ash from the agricultural industry, etc. In order to obtain AAB, the aluminosilicate precursors are activated with an alkali medium that results in dissolution of ions and formation of a gel that hardens. Though a significant improvement in the sustainability of concrete can be achieved with the use of AABs, the use of certain activators

Table 1
Merit/demerit of some common materials in green concrete.

Material	Merit/demerit	source
Rice husk ash (powder)	A good material for alkali activated binder or for supplementary cementitious material use.	[45]
Fly ash (powder)	It has dominated the effect on influencing permeability and compressive strength.	[46,47]
Silica fume (powder)	Less than 30% content can be useful for enhanced strength and durability property of concrete	[48]
Plastic	Improves impact resistance of concrete. Also, compressive strength of concrete increased with about 1% content of plastic.	[49,50]
Glass	Improves strength of concrete	[51]
Polyethylene (0 – 16 mm sizes)	Slightly improves the workability and air permeability in concrete, but causes reduction in concrete strength as its content increases.	[52]
Polypropylene (fibrous)	Have minimal effect on bond property of concrete. It however contributes to flexural strength of concrete.	[45,53]

might eliminate this advantage. This will be as a result of high embodied energy and carbon of the activators. However, this sustainability issue can be prevented with the use of activators with low embodied energy and carbon that will give similar or higher properties to those with higher embodied energy and carbon. The type of aluminosilicate precursor and alkali activator used are the factors that affect the properties of the AAB [27]. Sodium silicate and sodium hydroxide are the most common type of activator used in AAB due to its resulting high strength. The production of activators such as sodium silicate and sodium hydroxide consume a high amount of energy and release a consequential amount of carbon dioxide into the environment [28,29]. On the other hand, activators such as sodium carbonate occur naturally in the environment, and their processing consumes lower energy [30]. Therefore, in order to maximize the benefits of AAB to reduce carbon dioxide emission in the construction industry, activators with low embodied carbon and energy should be used. AAB has also been reported to have improved mechanical and durability properties.

2.3. Alternative cements

The use of calcium aluminate (CA) and calcium sulfoaluminate (CSA) cements is one of the pathways to produce green concrete. Jules Bied in France has invented calcium aluminate as early as the 1900 s, and this type of cement is comprised mainly of monocalcium aluminate, and other compounds in small quantities [31]. The use of this type of cement instead of OPC leads to green concrete because its production releases less amount of carbon dioxide into the environment. The sole purpose for which calcium aluminate cement was developed initially is to prevent sulphate attack on concrete. However, due to its sustainable advantage, it has been used for constructions in locations where sulphate resistance is not a concern. These types of cement also have other durability advantages such as improved resistance to abrasion and alkali-silica reaction. In addition, their rapid strength gain makes it suitable for certain type of construction. However, some of the alternative types of cement are more expensive than OPC, which has limited its use despite its possible contribution to obtaining green concrete [32]. It is worthy of mention that, fly ash has been tested as a binder suitable for enhancing the compressive strength and toughness of cementitious composite [33].

2.4. Waste materials as aggregate in concrete

Several solid waste materials are being generated by several industries, and most of these wastes are deposited in landfills or in open space where they pose a contamination threat to the environment. On the other hand, the production of concrete consumes a large amount of aggregates annually, and the natural sources of aggregates might not be able to meet up with the progression in the demand for concrete. Therefore, it is imperative to use other materials from other sources to complement the supply from the natural sources. Utilization of various solid wastes as aggregate in the production of concrete will results in a green concrete as it will eliminate the need to mine and process the natural aggregates. Also, use of these solid wastes as aggregate in concrete will help in conserving the natural sources of aggregates, managing waste, and reducing the overall embodied energy and carbon of concrete. Several solid wastes have been reported to be used as aggregate in concrete. Some of these wastes are; plastic [34], construction and demolition wastes [35], glass [36], agricultural wastes [37], slag [38], and ceramics [39]. However, the resulting effect of each type of waste used as aggregate varies from each other depending on the replacement level and physical properties of the aggregate. For example, the use of glass as partial replacement of fine aggregate in the range of 7.5 – 25% has been found to enhance the freeze and thaw resistance and surface scaling of concrete [40]. The use of glass as an aggregate at higher levels have been reported to result in a decrease in slump and reduction in mechanical properties [41].

The green concrete can be seen as an energy-efficient [42,43], and a technology with lesser environmental impacts. Many polymer matrices like, polyethylene and polypropylene were investigated for use in the field of green composites in recent years. Polyethylene have been mostly used as aggregate while polypropylene functioned more as reinforcing fibres in concrete. According to a report by Zéhil et al. [44], there was a marginal effect of polyethylene on workability and air permeability of concrete. However, the study showed that increasing content of polyethylene resulted in lowering both strength and shrinkage of the concrete. Other similar studies, have also reported the suitability of polyethylene and polypropylene for concrete production [45–47]. A summary of merit/demerit of some common materials in green concrete are presented in Table 1.

2.5. Wastewater

The high consumption of fresh water by concrete production has made it sustainable especially in parts of the world where there is a limited supply of fresh water. Use of water is essential in concrete as it serves as one of the reactants for the hydration reaction and a medium of transportation for ions. As water cannot be eliminated from the production of concrete, the use of wastewater instead of fresh water is one of the ways forward to achieve a green concrete. The possibility to use wastewater in concrete will ensure that there's enough supply of fresh water for consumption by living things. However, before wastewater can be used in concrete, it has to be recycled by treating it appropriately, as deleterious compounds in the wastewater can alter the chemical reactions going on inside the concrete.

3. Conclusions and future perspectives

A review of recent developments in the field of green concrete was presented in this study. It can be deduced that, the production of green concrete is not only beneficial to creating a sustainable and resilient infrastructure, but it will help to meet the future demand for concrete, which will aid more development and urbanization. Based on this review, the following conclusions can be drawn:

1) Green concrete offers a sustainable stream to meet the future demand for concrete, and provide a strong and durable construction material for future design requirements. In addition, green concrete provides a cheaper source of building material that will propel more development especially in developing countries.
2) As waste materials are effectively incorporated into green concrete, green concrete offers an avenue for management of waste materials that might have caused detrimental effects on the environment due to their improper disposal. In addition, use of these wastes in concrete conserve land spaces in which they will have been disposed of.
3) As the improper use of SCMs as a partial replacement for OPC can result in a different negative effect on the fresh and hardened properties of concrete, use of these SCMs in optimized levels will ensure favourable properties while reducing the overall carbon dioxide emission of concrete's production.
4) Alkali-activated binders are a viable replacement of OPC as a binder in concrete. However, in order to achieve green concrete with these types of binders, activators with low embodied energy and carbon has to be used.
5) More research in this field, alongside the development of standards for green concrete, will increase the confidence of construction stakeholders in the material. This will eventually lead to more application of green concrete for different infrastructure.

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