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Designing more sustainable and greener self-compacting concrete

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HIGHLIGHTS

- The environmental impacts of SCCs with different mixing proportions were investigated.
- The relationships between environmental impact and compressive strength of SCC were analyzed.
- Some suggestions for designing more sustainable and greener SCC were proposed.

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ABSTRACT

The present paper focuses on understanding the relationship between the mixing proportion parameters of self-compacting concrete (SCC) and its environmental impact and thus developing more greener SCC. Three simple indices combining the embodied environmental impacts with engineering properties (such as strength) of SCC are proposed. And 16 SCC mixtures with different compositions are designed to quantitatively evaluate the corresponding environmental impacts of SCC by use of the proposed index. Results indicate the ecological impact index of SCC closely depends on the mixing proportions. The addition of high volume mineral admixtures not only can effectively reduce the e-CO_2 and e-resource indices but also decrease the e-energy index. Selecting a reasonable aggregate volume can help decrease the environmental impact of SCC. Employing recycled limestone sand to replace river sand will increase the e-CO_2 index and e-energy index of SCC, although it can reduce the e-resource index. Regardless of the mixing proportion parameters, the e-CO_2, e-energy and e-resource index of SCC both decrease with the increasing compressive strength for SCCs with a compressive strength ranging from 30 to 60 MPa.

1. Introduction

Concrete is one of the most widely used building materials with a global consumption rate approaching 25 gigatons (Gt) per year [1,2]. CO_2 (from industries and the use of fossil fuels) emitted from concrete production and transportation is estimated to be approximately 10% of the total man-made CO_2 in the atmosphere [3]; consequentially, its environmental burden is significant in terms of environmental emissions, energy consumption and resource use. For these reasons, the sustainable development of concrete has received widespread attention; domestic and foreign scholars have conducted a series of investigations and explorations on green concrete [4–8] and, thus, vigorously promoted the development of greening technology for concrete. In China, Zhongwei first proposed the concept of 'green high performance concrete' in the 1990s, pointing out that green high performance concrete is the future of concrete development [9]. A diverse audience of decision makers and manufacturers are interested in understanding and lowering the environmental impact of concrete and other buildings materials, which requires a life-cycle assessment (LCA) approach [2,10]. Various strategies have been followed, separately or in combination, to improve the sustainability of concrete and even to develop green or ecological concrete. These strategies consist of incorporating recycled materials in concrete, optimizing the mix design, reducing CO_2 emissions by decreasing the Portland cement content, partially replacing Portland cement with cementitious by-product materials, increasing the durability of concrete to extend its service life and to reduce long-term resource consumption, and selecting low impact construction methods.

As one of the great innovations in concrete technology, self-compacting concrete (SCC) is in the process of casting without imposing additional vibrating forces, and only gravity is necessary to completely fill the mold cavity to form a uniform dense concrete [11,12]. Compared with traditional vibrated concrete, SCC has obvious advantages in terms of reducing construction costs and improving the construction environment, which are significant forward steps in the direction of sustainably developed concrete.

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However, compared to the vibrated concrete, unit SCC often requires higher volume binder levels (cement and cementitious materials) in the present technology. This will not only increase the cost of SCC but also significantly elevate its environmental burden. Therefore, some researchers have recently focused on the development of an eco-friendly version of SCC [13–16]. Wallevik et al. proposed the classification for SCC in terms of binder content [13]. They also defined the Eco-SCC as an economical and environmentally advantageous alternative to traditional vibrated concrete, in which the total powder content (cement, GGBS, fly ash, silica fume, limestone filler) is 315 kg/m^3 or below. Mansour et al. presented the distinctive balance between the sustainability pillars using the innovative EcoCrete and EcoCrete-Xtreme mixes [14]. The EcoCrete and EcoCrete-Xtreme SCC mixes were designed to have very to extremely low Portland cement and binder contents, respectively. However, the breakdown of materials used in both mixes remains undisclosed. Sahmaran et al. [15] investigated whether spent foundry sand can be successfully used as a sand replacement material in cost-effective, green SCC. In their research, the SCC mixtures were developed to be even more inexpensive and environmentally friendly by incorporating Portland cement with fly ash. As mentioned above, there are some new achievements with respect to the environmental impact of SCC. However, the published documents on the environmental impact assessment of SCC are still somewhat limited, and more detailed research is needed to further promote the sustainable development of SCC and to enrich the content of eco-SCC.

The present paper focuses on understanding the relationship between the mixing proportion parameters of SCC and the environmental impact of SCC and, thus, further develops a new eco-SCC mix design method. For this reason, three simple indices combining the embodied environmental impacts with engineering properties (such as strength) of SCC are proposed. Then, 16 SCC mixtures with different compositions are designed to quantitatively evaluate and compare the corresponding environmental impacts of SCC by use of the proposed index. Finally, some useful suggestions for reasonably designing eco-SCC are presented.

2. Methodology

2.1. Experimental design

Briefly, the experiments were designed to determine how the mixing proportions of SCC influence its greenness and to compare the environmental impacts of various SCCs with different compositions of raw materials. The raw materials used in this experiment include cementitious materials, river sand (S) with a fineness modulus of 2.86 or recycled limestone sand with a fineness modulus of 3.0 produced by quarry waste-limestone-chip, crushed limestone (G) with a size of 5–20 mm, water (W) and chemical admixtures. Ordinary Portland cement (C) with a compressive strength grade of 42.5 MPa, Class I fly ash (F), granulated blast furnace slag (GGBS), and ultrafine metakaolin (M) with a size of 2000 mesh were used as the cementitious materials. Limestone powder (LP), which originates from grounded quarry waste-limestone-chips, was used as inert filler. The chemical compositions of the mentioned cementitious materials are shown in Table 1. The chemical admixtures used included polycarboxylate superplasticizer (SP) with a water-reducing rate of 26%, hydroxypropyl methyl cellulose (viscosity modified agent, VMA) and alkylbenzene sulfonate air-entraining agent (AE), aiming to achieve a pleasing workability for fresh concrete. Tap water was used as the mixing water.

Table 1
Physical and chemical compositions of cementitious materials.

Item	Chemical compositions/by wt%						Specific area (m^2/kg)
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	
Cement	21.3	5.8	3.9	59.7	3.4	2.3	335
Fly ash	52.7	25.9	9.7	3.7	1.2	0.2	430
Granulated slag	34.2	13.8	15.3	26.6	8.1	–	415
Metakaolin	55.2	42.5	1.3	0.5	0.1	–	–
Limestone powder	–	–	–	50.3	2.8	–	390

To reach the above goal and for better analysis of the greenness of concrete prepared by different proportioning parameters, we designed sixteen SCC mixtures with medium strength grade, including four series. To cover the main SCC types used in practice, different factors in these concretes are considered, including the type of mineral admixtures, replacing the ratio of mineral admixtures, using recycled limestone powder as the inert filler and including recycled limestone sand from quarry waste-limestone-chip, as well as the chemical admixture of VMA and AE. The first SCC serial (C1–C10) covers the concretes incorporated with various mineral admixtures by replacing 25% and 50% of the cement. The second serial (C10–12) covers the SCC samples with aggregate volume fractions ranging from 0.6 to 0.64. The third serial (C13) has 5% air content by adding AE agent to reduce the content of cementitious materials in SCC. The fourth serial (C14–C16) covers the SCC samples prepared by using recycled limestone sand to replace river sand. The mixing proportions of the different concrete mixtures are shown in Table 2.

The workability, such as slump flow, T_{500} and visual stability index (VSI) in the fresh state and compressive strength at 28-day age of all concrete were tested and are listed in Table 3. The workability of fresh concrete was tested according to ASTM C1611. The cubic compressive strength of concrete was tested according to the Chinese National standard GB/T50081-2002. From the results of property of each SCC shown in Table 3, it can be found that each fresh SCC possesses high flowability and excellent segregation resistance. And the compressive strength of hardened SCCs ranges from 30 MPa to 60 MPa.

2.2. Embodied environmental impact evaluation of SCC

It is well known that the environmental impact evaluation of concrete over its entire life cycle is complex because many factors affect the final evaluating value. In particular, it is very difficult to give a credible life cycle inventory analysis for the concrete life cycle assessment approach [2]. In spite of this, some researchers still have concentrated on the embodied carbon dioxide (EC) of concrete, given the growing concern over the global warming impact of the built environment. EC is the carbon dioxide emitted as a result of material processing and transport, construction, and decommissioning and demolition and is analogous to a fixed capital cost [17]. Recently, commentators have published EC values for concrete, either as individual values or a small range depending on certain properties (mainly compressive strength grade and the use of Supplementary cementitious materials). Hammond and Jones [18] described a monotonic relationship between EC (0.061–0.188) and characteristic cube strength (8–50 MPa) for CEM I and CEM II concretes. Meanwhile, Hacker et al. [19] used a value of 0.200 with no strength discrimination, while Harrison et al. [20] used 0.13 for plain concrete and 0.24 for '2% reinforced' with the additional CO_2 attributable to the steel. Among those values reported on a volumetric basis, Flower and Flower [21] used values of 0.225–0.322 kg/m^3 for normal and blended cement concretes, corresponding to an EC of 0.09–0.12. Purnell et al. reported on the variation of embodied carbon dioxide in concrete with common mixing proportion parameters. They also analyzed the carbon footprint of reinforced concrete based on the 'functional unit' method [22]. However, none of these studies provided results on the embodied environmental impact of SCC. Moreover, detailed quantitative analysis related to the energy consumption and resource usage of concrete during production, transport and construction is limited.

Based on the above analysis, we investigated the environmental impact of unit SCC (per m^3) from three aspects: CO_2 emissions, energy consumption and primary natural resource expenditure. Thus, three indices, including the embodied CO_2 index (e-CO_2 index, CI), embodied energy index (e-energy index, EI) and embodied primary natural resource (e-resource index, RI), were proposed to assess the greenness of unit SCC. The three indices were obtained by considering a combination of the environmental efficiency and the comprehensive engineering properties of SCC (i.e., cubic compressive strength), as demonstrated in the following Eqs. (1–3):

$$CI = \frac{\text{embodied} - CO_2\ (\text{kg/m}^3)}{\sigma\ (\text{MPa})} \tag{1}$$

$$EI = \frac{\text{embodied} - \text{energy}\ (\text{MJ/m}^3)}{\sigma\ (\text{MPa})} \tag{2}$$

$$RI = \frac{\text{embodied} - \text{primary} - \text{resources}\ (\text{kg/m}^3)}{\sigma\ (\text{MPa})} \tag{3}$$

The embodied CO_2 emissions and embodied energy consumption are calculated by considering all major emissions or consumptions during the extraction of raw materials, transportation to the site, construction processes and so on but not post-installation operations, e.g., demolition, because these are generally not significant [17]. The environmental impact value of SCC coming from the raw materials, i.e., the value of embodied CO_2 of SCC from each raw material, can be obtained by totaling the multiple emissions of embodied CO_2 per unit and the mass of each raw material in SCC per m^3. The embodied environmental impact of each raw material of SCC used in this paper, as shown in Table 4, refers to the available authoritative data in the open literature [7,17,22,23–27]. The energy consumption of