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Sustainable SCC with high volume recycled concrete aggregates and SCMs for improved mechanical and environmental performances

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Abstract. Using industrial wastes and construction and demolition (C&D) wastes is potentially advantageous for concrete production in terms of sustainability improvement. In this paper, a sustainable Self-Compacting Concrete (SCC) made with industrial wastes and C&D wastes was proposed by considerably replacing natural counterparts with recycled coarse aggregates (RCAs) and supplementary cementitious materials (SCMs) (i.e., Fly ash (FA), ground granulated blast furnace slag (GGBS) and silica fume (SF)). A total of 12 SCC mixes with various RCAs and different combination SCMs were prepared, which comprise binary, ternary and quaternary mixes. The mechanical properties in terms of compressive strength and static elasticity modulus of recycled aggregates (RA-SCC) mixes were determined and analyzed. Microstructural study was implemented to analyze the reason of improvement on mechanical properties. By means of life cycle assessment (LCA) method, the environmental impacts of RA-SCC with various RCAs and SCMs were quantified, analyzed and compared in the system boundary of "cradle-to-gate". In addition, the comparison of LCA results with respect to mechanical properties was conducted. The results demonstrate that the addition of proposed combination SCMs leads to significant improvement in mechanical properties of quaternary RA-SCC mixes with FA, GGBS and SF. Furthermore, quaternary RA-SCC mixes emit lowest environmental burdens without compromising mechanical properties. Thus, using the combination of FA, GGBS and SF as cement substitution to manufacture RA-SCC significantly improves the sustainability of SCC by minimizing the depletion of cement and non-renewable natural resources.

Keywords: environmental impacts; life-cycle assessment (LCA); mechanical properties; recycled coarse aggregates (RCAs); self-compacting concrete (SCC); supplementary cementitious materials (SCMs)

1. Introduction

China has witnessed an economic boom and rapid urbanization development during the last two decades, consequently promoting the large-scale construction of infrastructure and engineering projects. However, the cumulative environmental burdens in the construction process resulted in severe damage to ecosystems and human health. Due to its many advantages, such as low cost, superior mechanical and durability properties, good fire resistance, and ease of molding into different sizes and shapes, concrete is used in various structures. It is the most commonly used building material in China's construction industry (Liu *et al*. 2020). In 2019, the estimated concrete consumption was 2.0-2.1 billion cubic meters in China. As a result, the consumption of non-renewable natural resources (limestone and river sand), which is the major component in concrete mixes, and the generation of construction and demolition (C&D) wastes rapidly increased in China. For instance, it was roughly predicted that China's construction sector consumed about 15 billion tons of natural gravels and sands and generated a total of about 1.55-2.4 billion tons of construction waste in 2019, contributing to serious environmental issues in terms of overexploitation of natural resources and environmental pollution (Zhang *et al*. 2019).

There are several benefits (i.e., preservation of non-renewable natural resources and landfills) with respect to recycling C&D wastes as aggregates to produce recycled aggregate concrete (RAC), which is an effective method to reduce the environmental issues in concrete production and enhance the sustainability aspect of the construction sector (Teh *et al*. 2018). Over the past two decades, many programs have been performed to investigate the performance of RAC and its structures. Recently, RAC has been successfully used in practical engineering applications in China (Xiao *et al*. 2016). Fayed *et al*. (2023) investigated the bond behavior of passively confined-recycled aggregate concrete using center pull-out tests on deformed steel bars, showing significant improvement with steel mesh fabric (SMF) confinement. A formula to predict the ultimate bond strength of RAC considering concrete strength grade, RCA content, SMF confinement, and transverse ties was proposed. Mansour and Fayed (2021) compared the mechanical properties of concrete reinforced with recycled plastic (RP) or end-hooked steel (EHS) fibers at volume fractions of 1%, 2%, and 3% and concluded that RP and EHS fibers significantly improved the mechanical properties of concrete and the flexural capacity of reinforced concrete beams.

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It is well known that concrete production depletes large quantities of energy and releases considerable amounts of carbon dioxide, resulting in serious environmental issues primarily in relation to greenhouse gas (GHG) emissions (Singh *et al*. 2017, Li *et al*. 2019). It is roughly predicted that the GHG releases from the construction sector is responsible for nearly half of the world's emissions. Therefore, considering its widespread use as well as resulting severe damage to the environment, it is imperative to properly evaluate the environmental burdens of concrete, so as to seek a novel method to enhance the sustainability aspect of concrete and maintain the competitiveness as a construction material in the future, focusing on the preservation of non-renewable natural resources and the mitigation of GHG emissions (Tabatabaei 2019, Teixeira *et al*. 2016).

In recent years, the environmental impact assessment of concrete has gained much attention, and several methods have been proposed to decrease the environmental impacts of concrete production. The research on the environmental burdens of concrete is of remarkable importance considering the huge volume of concrete used and the increasing importance of environmentally sustainable concrete structures. Several investigations have focused on the environmental impact assessment of "green" concrete mixes, such as geopolymer, Fly ash (FA), or slag concrete (Celik *et al*. 2015, Estanqueiro *et al*. 2018, Gursel *et al*. 2016, Kurtoglu *et al*. 2018, Teh *et al*. 2017). The majority of the previous studies showed that cement production contributes most to the whole environmental burdens of concrete production and the environmental performance of the concrete is strongly dependent on the cement content. Thus, the use of industry by-products, such as FA, slag as cement substitution in concrete manufacture can effectively reduce CO_2 emission and the disposal of industrial wastes, thereby relieving the environmental burdens and making it possible to produce more eco-friendly concrete (Guo *et al*. 2018, Miller 2018, Oliveira *et al*. 2016, Pradhan *et al*. 2019, Zhang *et al*. 2019). An experimental study conducted by Celik *et al*. (2015) indicated that substituting cement with FA or/and limestone powder produced high-strength concrete with superior workability and low GHG emissions. Gursel *et al*. (2016) studied the mechanical and environmental performances of eco-friendly concrete with FA, limestone powder and rice husk ash and found that ternary and quaternary mixes blended with rice husk ash and FA emitted the lowest global warming potential (GWP) without compromising mechanical and durability properties. Teh *et al*. (2017) studied the GHG emission of geopolymer concrete containing FA, SL, and found that using geopolymer reduced the GHG emissions. Kurda *et al*. (2018) studied the environmental performance of high-content FA concrete and concluded that concrete mixes blended with FA resulted in fewer adverse effects on the environment in comparison with reference concrete. Chen *et al*. (2019) found that the GHG emissions of three types of pervious concrete mixes containing slag or FA declined by 11-19% in comparison with companion normal concrete mix. Kurda *et al*. (2020) calculated the environmental impacts of high-content FA and RAC and concluded that the environmental burdens remarkably declined with the addition of FA, regardless of the transportation scenario. Lovecchio *et al*. (2020) evaluated the environmental impacts of concrete with supplementary cementitious materials (SCMs) and engineered nanomaterials (ENMs) and concluded that the addition of SCMs and ENMs declined the GWP of concrete production without compromising strength and durability.

More recently, the environmental benefits of the use of recycled coarse aggregates (RCAs) in concrete production have been confirmed (Ding *et al*. 2016). Extensive life cycle assessment (LCA) studies indicated that the clear environmental advantages in RAC manufacture were primarily related to the declined impacts associated with the avoided disposal of C&D waste and the minimization of natural resource depletion (Estanqueiro *et al*. 2018). In addition, LCA results also revealed that coarse aggregate is commonly the second largest contributor to environmental impacts and the transport stage influences the overall environmental burdens, which are mainly depended on the transport distances and the type of vehicle (Gayarre *et al*. 2016). Several environmental impact categories, such as energy use, global warming, eutrophication, and acidification, depend primarily on transport distances and types of aggregates. Therefore, when the recycling plants are situated in the vicinity of the concrete plants, the environmental advantages for the production of RAC are only available.

2. Research objectives significance

Currently, most researchers only investigate the effects of recycled aggregates (RA-SCC) from one perspective of concrete, such as mechanical performance or LCA (Campos *et al*. 2018, Fiol *et al*. 2018, Kurda *et al*. 2018, Miller 2018). However, to ascertain the benefits of using SCMs and RA in concrete, it is necessary to conduct a comprehensive analysis of RA-SCC through both mechanical performance and LCA. Therefore, this study aims to fill the aforementioned gap by comparing the separate and combined effects of SCMs and RA on the mechanical and environmental performance. The comparison of LCA results with respect to mechanical properties was also conducted, thus revealing the optimal mixture of RA-SCC with superior mechanical and environmental performance.

Previous studies indicated that the use of industrial by-products and C&D wastes as raw material substitution is environmentally advantageous for concrete production in terms of sustainability improvement. The aim of this research is to enhance the sustainability performance of Self-compacting concrete (SCC), focusing on the replacement of high-volume cement and natural aggregates with industrial by-products and RCAs, thus restricting the depletion of non-renewable natural resources and cement as well as minimizing waste and its related emissions. In this paper, 12 RA-SCC mixes, which comprise binary, ternary and quaternary mixes, were manufactured by considerably substituting natural aggregates with RCAs and cement with

SCMs. The mechanical properties, in terms of compressive strength and static elastic modulus of RA-SCC with various RCAs and different combination SCMs, are analyzed as well as the effect of RCAs and SCMs. In addition, a microstructural study using a scanning electron microscope (SEM) was implemented to investigate the reason for the improvement in the mechanical properties of RA-SCC. At last, the environmental impacts from the production of RA-SCC mixes with various RCAs and different combination SCMs are quantified, analyzed and compared in the system boundary of "cradle-to-gate", by adopting LCA methodology. The major contribution to the environmental impacts was analyzed in detail as well as the effect of RCAs and SCMs. The comparison of LCA results with respect to mechanical properties was also conducted.

3. RA-SCC mixtures

The sustainable RA-SCC was produced by replacing natural coarse aggregates (NCAs) and cement with high-volume RCAs and SCMs, respectively. Mineral additives, such as fly ash (FA), ground granulated blast furnace slag (GGBS), and silica fume (SF) are in general well-known to influence the durability performance and strength of the concrete. In this research, cement was substantially replaced with an integration of FA, GGBS and SF, which is expected to enhance the mechanical properties and the durability of RA-SCC. The commercial productions of mineral additives (FA, GGBS, SF) and cement with a 28d nominal compressive strength of 42.5 MPa were adopted as binders. The physical and chemical properties of cement and Mineral additives were studied and are listed in Table 1. The NCA was crushed limestone with a maximum particle size of 20 mm. River sand was adopted as natural fine aggregate (NFA). The apparent density, water absorption in saturated surface dry (SSD) condition as well as fineness modulus of NFA was 2610 kg/m^3, 1.1% and 2.43, respectively, which were measured in accordance with Chinese code (JGJ 52-2006) (Chinese Standard 2006).

Table 1 Physical properties and chemical analysis of OPC, FA, GGBS, SF

Compounds	Cement	FA	GGBS	SF
SiO_2	19.73	52.79	31.76	95.48
CaO	64.73	5.61	44.01	0.44
Al_2O_3	4.78	24.47	13.82	0.40
Fe_2O_3	3.87	8.58	1.58	0.03
SO_3	2.47	0.62	1.47	0.42
MgO	2.05	0.90	5.63	0.40
K_2O	0.50	1.37	0.39	0.25
Na_2O	0.10	0.66	0.34	0.32
Loss on ignition	1.10	3.51	2.27	0.90
Specific surface area (m^2/kg)	410	3000	520	20000
Specific gravity	3.12	2.43	2.85	2.08

RCAs were produced from demolished concrete elements, and the maximum and minimum particle sizes of RCAs were 20 mm and 5 mm, respectively. The surface gravity of natural and recycled coarse aggregate was 2698 and 2594 kg/m^3, respectively, and the water absorption at SSD condition of natural and recycled coarse aggregate was 0.5 and 4.9%, respectively. The chemical admixture adopted was polycarboxylate superplasticizer (SP). The specific gravity of SP was between 1.010 and 1.120.

The proportions of sustainable SCC mixtures blended with various RCA and Mineral additives are shown in Table 2. In order to evaluate the environmental performance of RA-SCC mixtures with varying SCM types and various combination types, a total of 12 mixes were manufactured in this test, which comprise binary, ternary and quaternary mixes. Binary mixes were prepared with cement partially replaced with FA and ternary mixes were blended with FA and GGBS. The water/binder (w/b) ratio of all SCC mixtures was 0.35. The total aggregate-to-binder ratio ranges from 3.1:1 to 3.2:1 by weight. Two replacement levels of RCA (i.e., 50% and 100% (by weight)) and two replacement ratios of SCMs (i.e., 50 and 75% (by weight)) were adopted in this study, which aims to study the rate of change in the environmental burdens in relation to the form and amount of replacement for cement and natural aggregates. Specimen 0-0 with 100% cement and natural aggregates are served as the reference mix. The higher water absorption ability of RCAs resulted in an extra amount of free water added to the RA-SCC mixtures, as given in Table 2.

The proportioned materials were mixed in a drum mixer. First of all, RCA, NCA, NFA, SCMS and OPC were placed into the mixer and dry mixed for 2 minutes. Then, 90% of the water was added and mixed for 2 minutes. Finally, the rest of the water and superplasticizer were added and continued to mix. The mixture was fabricated in the steel molds without compaction and vibration. After that, all concrete specimens were cured in a room with a temperature of (20 ± 5)°C for 24 hours; then, all specimens were demolded and cured in a standard environment (i.e., an average temperature of 20 ± 2°C and relative humidity of 95%).

4. Mechanical properties of RA-SCC mixtures

For an accurate comparison of LCA results with respect to mechanical properties, several concrete properties (i.e., strength and elastic modulus) should be determined prior to LCAs. Thus, the compressive strength and modulus of elasticity of all RA-SCC mixtures were determined and analyzed firstly. Table 3 summarizes the 14, 28, 56 and 112-day compressive strength of RA-SCC, which is the average value of three samples each time.

The relationship between the RCA replacement ratio and strength of SCC specimens is depicted in Fig. 1. The compressive strength of Non-SCM RA-SCC specimens decreases as RCA content increases, as shown in Fig. 1. Compared to the companion mix 0-0, the reduction of compressive strength of nix with 50% RCA and 100% RCA is 12.9% and 17.9%, respectively, which is primarily

Table 2 Concrete mixture proportions (kg/m^3)

Concrete mixes	Cement	FA	GGBS	SF	Water	NCA	RCA	Sand	SP	Additional water
0-0	520	0	0	0	182	867	0	785	4.02	0
50-0	520	0	0	0	182	433	416.4	785	4.16	24.7
100-0	520	0	0	0	182	0	832	785	4.72	32.9
50-50-1	260	260	0	0	182	433	416.4	785	5.72	24.7
50-50-2	260	130	130	0	182	433	416.4	785	5.43	24.7
50-50-3	260	104	104	52	182	433	416.4	785	6.76	24.7
50-75-1	130	390	0	0	182	433	416.4	785	5.94	24.7
50-75-2	130	195	195	0	182	433	416.4	785	4.68	24.7
50-75-3	130	169	169	52	182	433	416.4	785	6.80	24.7
100-75-1	130	390	0	0	182	0	832	785	7.40	32.9
100-75-2	130	195	195	0	182	0	832	785	7.28	32.9
100-75-3	130	169	169	52	182	0	832	785	7.57	32.9

Table 3 Mechanical properties for RA-SCC mixes

Concrete mixture	$f_{cu,14}$ MPa	$f_{cu,28}$ MPa	Elastic modulus GPa	$f_{cu,56}$ MPa	$f_{cu,112}$ MPa
0-0	39.33	53.45	38.83	54.65	56.33
50-0	43.16	46.54	34.96	50.26	53.12
50-50-1	17.08	18.04	19.21	26.37	38.06
50-50-2	31.20	33.51	29.27	39.55	47.27
50-50-3	38.04	40.31	33.98	46.08	54.00
50-75-1	5.36	7.17	14.39	12.66	22.85
50-75-2	18.27	19.66	17.28	24.63	31.44
50-75-3	29.93	38.54	32.79	44.43	52.76
100-0	-	43.89	33.67	-	-
100-75-1	-	13.64	21.57	-	-
100-75-2	-	30.84	28.48	-	-
100-75-3	-	42.75	33.35	-	-

attributed to the weaker strength as well as more porous structure of RCA in comparison with natural aggregates.

Fig. 2 shows the effect of the SCM replacement level on the compressive strength, where compressive strength is depicted against the SCM replacement ratio at various RCA content and various SCM combination types. As can be seen from Fig. 2, the compressive strength of binary and ternary specimens decreases with the SCM replacement ratio increasing. This is primarily due to the limited CaO of SCMs, which delayed the hydraulic reaction. In addition, as can be seen from Fig. 2, the compressive strength of quaternary RA-SCC mixtures with FA, GGBS, and SF is similar to that of companion normal mix, which demonstrates that substituting cement using a combination of SF, FA, and GGBS enhance the compressive strength of RA-SCC mixes.

Fig. 3 illustrates the effect of SCM combination type on the strength of SCC specimens. It is obvious from Fig. 3 that at a given SCM replacement level, SCC mixes blended with FA, GGBS and SF achieve the highest compressive strength, followed by ternary mixes, whereas binary mixtures reach the least compressive strength. In comparison with binary mixes, the compressive strength increment of quaternary mixtures ranged from 123% to 496%. According to the test results, it can be concluded that replacing cement with a combination of SF, GGBS and FA considerably enhanced the compressive strength of SCC mixtures with RCAs. This is mainly due to the pozzolanic reaction and hydraulic activity of mineral additives and the synergistic effect between these mineral additives with different particle sizes (FA, GGBS, and SF), resulting in a more compact microstructure and higher packing density. A similar result was also obtained by Celik *et al.* (2015) that the synergistic effect in SCC mixture blended with cement, FA, and limestone powder enhanced the mechanical properties of concrete mixtures.

As can also be seen from Table 3, the development of early compressive strength of non-SCM SCC mixes is faster than that of SCM SCC. This is attributed to the higher CaO content, which resulted in rapid hydraulic reaction (Hu 2018). The pozzolanic reaction of FA is relatively slow, depending on the availability of calcium hydroxide, resulting in a slow strength development. Adekunle *et al.* (2015) and Djamila *et al.* (2018) also concluded that the

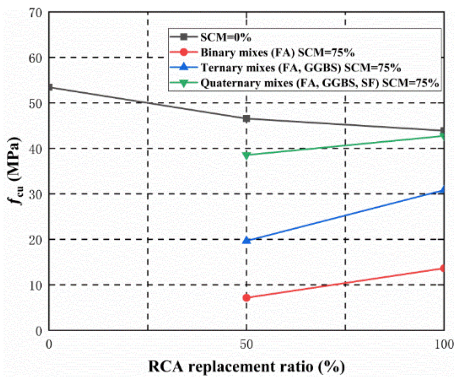

Fig. 1 Effect of RCA replacement ratio on the compressive strength

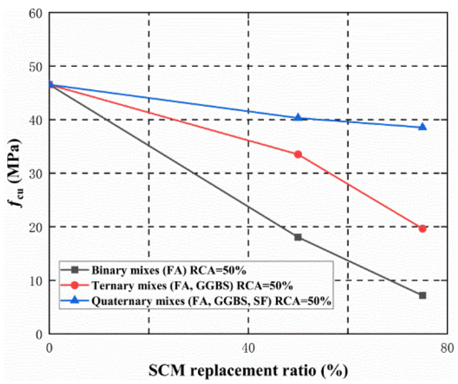

Fig. 2 Effect of SCM replacement ratio on the 28-day compressive strength

replacement of cement with SCM led to slow development of strength. Nevertheless, at later ages, the strength development of SCM-SCC mixtures is faster than that of SCC mixtures without SCMs, which is attributed to the onset of the pozzolanic reaction.

The static modulus of elasticity of RA-SCC mixes with various RCAs and SCMs was determined using cylinders with a diameter of 150 mm and a height of 300 mm, which is summarized in Table 3. It is obvious from Table 3 that the elastic modulus of RA-SCC decreased with the increase of quantity of RCAs. For example, the elastic modulus of mix 50-0 with 50% RCAs and 100-0 with 100% RCAs reduced by 10% and 13.3%, respectively, compared to control normal mix 0-0. This is due to the same reason as discussed for compressive strength. The old mortar paste adhered to the RCAs has a lot of pores and micro voids and cracks, thus resulting in the higher porosity and water absorption ability of the RCAs, which adversely influences the elastic modulus of RA-SCC mixes.

Additionally, as can be seen from Table 3, the addition of SCMs using different combination types significantly affects the modulus of elasticity of RA-SCC. The effect of combination type on the elastic modulus of RA-SCC is depicted in Fig. 4. It is obviously clear from Fig. 4 that substituting cement with a combination of FA, GGBS, and/or SF substantially increased the elastic modulus of RA-SCC mixes. With respect to RA-SCC mixes with various RCAs and SCMs, quaternary RA-SCC mixes with

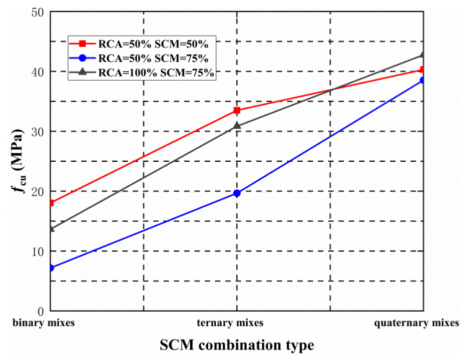

Fig. 3 Effect of SCM combination type on the 28-day compressive strength

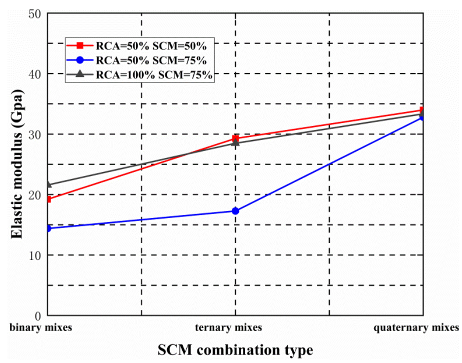

Fig. 4 Effect of SCM combination type on the elastic modulus

FA, GGBS and SF have the highest modulus of elasticity, followed by ternary RA-SCC mixes. Binary mixes with only FA are the least stiff ones. For example, quaternary mix 50-50-3 and 100-75-3 exhibit modulus of elasticity increases of 76.8% and 68.5% in relation to replicate mix 50-50-1 and 100-75-1, respectively. Mix 50-75-1 with 75% FA has the least elastic modulus. According to the test results, it can be concluded that the addition of SCMs using a combination type can offset some of the stiffness reduction because of the incorporation of RCAs, thus increasing the elastic modulus of RA-SCC mixes. The reason is the same as discussed in the case of cube compressive strength that the pozzolanic reaction and hydraulic activity of Mineral additives, as well as the remarkable synergistic effect between these components with different particle sizes, led to a more compact microstructure and higher packing density, thus resulted in a higher elastic modulus of RA-SCC mixes.

Several formulas for calculating the elastic modulus of concrete are available in the open literatures. The formula proposed by ACI 318-11 (ACI Committee 318-11 2011), Eurocode 2-04 (EN 1992-1-1 2004) is calculated as $E_c = 4.73\sqrt{f_c'}$; $E_c = 22(f_{cm})^{0.3}$, respectively.

Considering the elastic modulus of RA-SCC was significantly affected by RCAs and SCMs, the existing models need to be suitably modified for elastic modulus predictions. In this paper, based on Eurocode 2-04 (EN 1992-1-1 2004) model, an empirical formula was presented

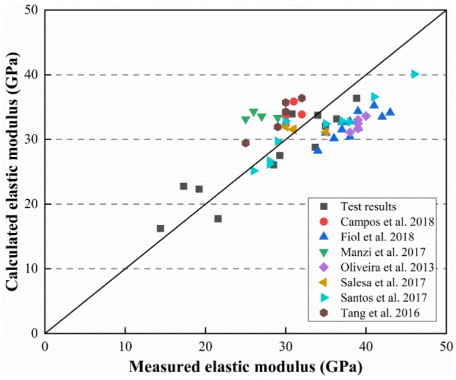

Fig. 5 Comparison of calculated elastic modulus and test results

to calculate the modulus of elasticity of RA-SCC mixes incorporating various RCAs and SCMs in this paper, by adopting a parameter to account for the effect of RCAs and SCMs, which is calculated as follows

$$E_c = (1 + A_0 R_{RCA} + A_1 R_{SCM}) 22 (f_{cm})^{0.3} \quad (1)$$

where f_{cm} is the compressive strength; R_{RCA}, R_{SCM} is the RCA and SCM replacement ratio, respectively. A_0 is the constant accounting for the effect of RCAs and was obtained by multivariable regression using test results, which is -0.16. A_1 is the constant accounting for the effect of SMCs and was obtained by regression using test results, which is -0.14, -0.10, 0.18 for the inclusion of FA, FA+GGBS, and FA+GGBS+SF, respectively.

The modified formula was verified using the test results obtained in this paper and open literatures (Campos *et al.* 2018, Fiol *et al.* 2018, Manzi *et al.* 2017, Pereira-De-Oliveira *et al.* 2013, Salesa *et al.* 2017, Santos *et al.* 2017, Tang *et al.* 2016). A comparison of the calculated elastic modulus using Eq. (4) with test results is conducted and shown in Fig. 5. It is clear from Fig. 5 that the calculated elastic modulus is in good agreement with the test results, indicating that the modified formula accurately predicts the elastic modulus of RA-SCC mixes.

5. Microstructure analysis

Microstructural study of RA-SCC using a scanning electron microscope can inspect the voids, cracks, and concrete paste quality on interfacial transition zone (ITZ), thus giving a clear photograph regarding the effect of RCA and SCM on the strength and elastic modulus of RA-SCC (Rajhans *et al.* 2018a, b).

Fig. 6 depicts the scanning electron microscope image of RA-SCC mixtures with various RCAs and SCMs. It is clear from Fig. 6(a) that more and wider cracks and pores were observed in the ITZ of RA-SCC mix without SCMs. Nevertheless, these pores and cracks are filled and decreased for RA-SCC mix with SCMs, especially for quaternary mixtures with FA, GGBS, and SF, as can be seen from Fig. 6(d). The cracks and pores are minimal in the case of RA-SCC specimens produced with FA, GGBS, and SF and maximum in the ITZ of RA-SCC without SCMs. Furthermore, loose paste occurs more for mix 50-0 in comparison with RA-SCC mixes with SCMs, as shown in Fig. 6. This can be interpreted that the cracks and pores observed for RA-SCC are filled and reduced after the addition of various SCMs, especially SF. SF reacts with unhydrated cement, thus generating the main hydration compound, namely C-S-H gel, which is an important constituent of the strength of concrete. C-S-H can bind the cement mortar and aggregate, thus enhancing the density of ITZ. In addition, SF, with a much finer particle size, fills the pores and cracks of ITZ, acts as a pore filler of cement paste, and creates dense packing. In particular, SF fills up the voids and weak areas of RCAs and thus enhances the old and new ITZ of RA-SCC, and a more dense and stronger microstructure is developed, resulting in the substantial improvement of mechanical properties of RA-SCC. Similarly, the pores in concrete paste are reduced because of the addition of SCMs. It can be concluded that the ITZ and paste of RA-SCC mixes are strengthened and become stronger and denser by the addition of FA, GGBS, and SF. The microstructural study using a scanning electron microscope justifies the improvement of mechanical properties because of the addition of SCMs using a combination type.

6. Life cycle assessment methodology

LCA methodology qualitatively and quantitatively quantifies, evaluates, and compares the environmental performance of services or products during their life cycle (including the extraction and acquisition of raw materials, use, end-of-life treatment, and final disposal) (Zhang *et al.* 2019). It quantifies both the input flows (i.e., materials, energy, and water) and the output flows (i.e., pollutant emissions, solid and liquid wastes), thereby assessing the potential impact on nature and humans and revealing policies that can optimize energy and material flows inside the analyzed system (Celik *et al.* 2015, Dossche *et al.* 2018, Gayarre *et al.* 2016). International standards ISO 14040 (International Organization of Standardization 2016) and ISO 14044 (International Organization of Standardization 2016) provided a detailed description of the LCA methodology, which consisted of terminology, method-logical phases and consensual framework as well as put forward that the LCA study generally consists of four phases (Goal and Scope Definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and Interpretation).

6.1 Goal and scope

The primary purpose of this study was to quantify and compare the environmental burdens related to the production of sustainable SCC mixtures with various RCAs and SCMs. The functional unit, depending on the objective of LCA research, is the foundation for comparison of the entire LCA study. (International Organization of Standardization 14040 2016, International Organization of Standardization 14044 2016) The functional unit adopted in

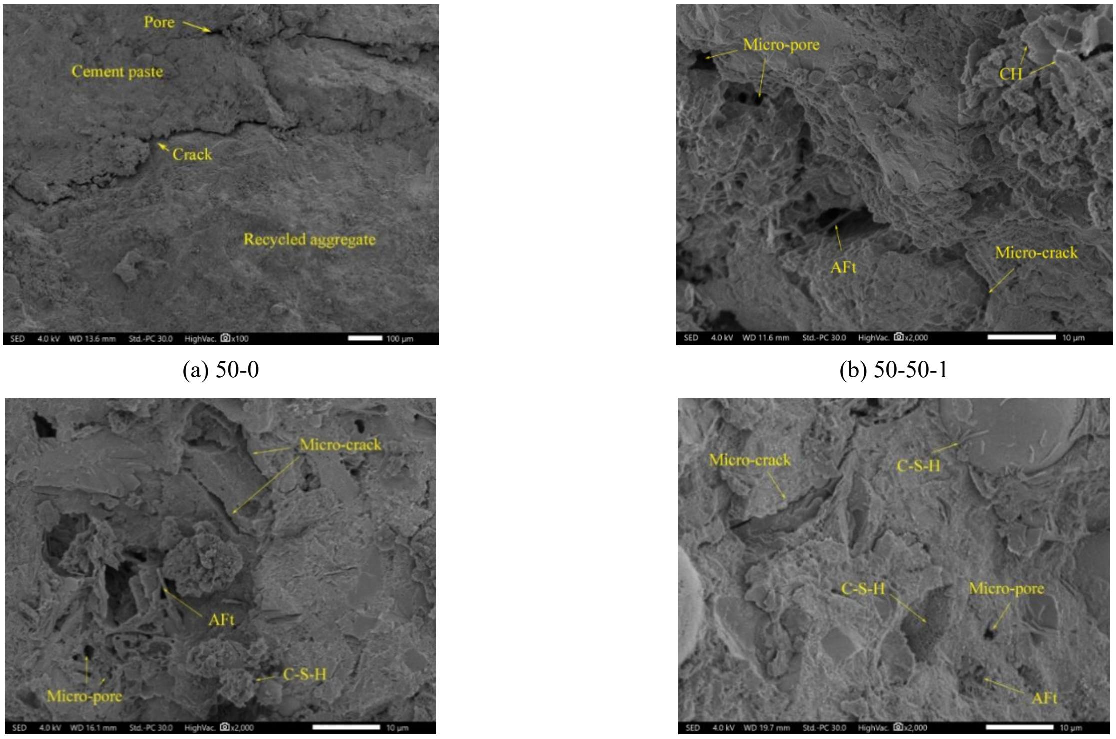

Fig. 6 Microstructural analysis of RA-SCC mixes

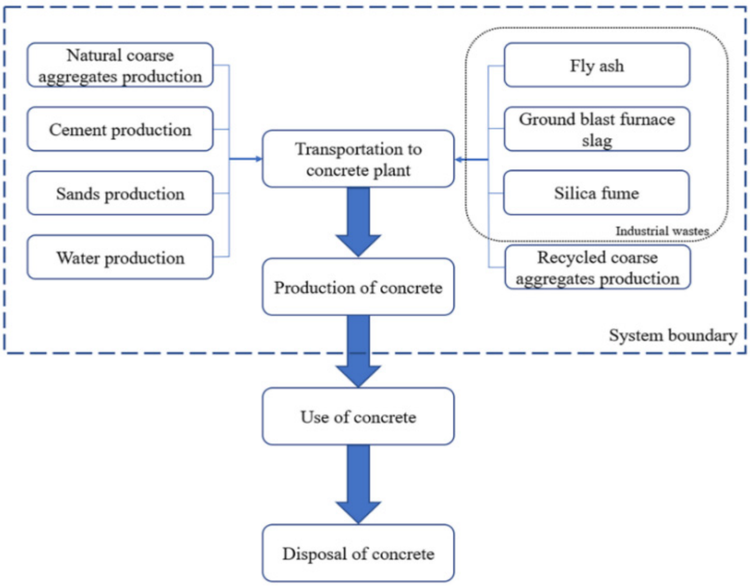

Fig. 7 System boundary of RA-SCC for LCA

this research was 1 m^3, which was widely used in the previous LCA studies. Using functional units (i.e., 1 m^3) as the benchmark for the sustainable SCC mixtures production process, all raw material inputs, energy consumption and waste output are calculated.

Three different system boundaries, namely cradle-to-gate, cradle-to-grave, and cradle-to-cradle were generally adopted for the LCA of the concrete industry. (Kurda *et al.* 2018, Vieira *et al.* 2016) Considering that RA-SCC and conventional concrete are designed to meet similar functional requirements and that the operations involved in the construction, service, and waste treatment process are expected to be roughly the same, the cradle-to-gate system boundary was adopted in this research. Fig. 7 shows the cradle-to-gate system boundary of RA-SCC, which includes the raw material production, material transportation, and the production of SCC mixtures at the gate of the concrete plant.

Table 4 Life cycle inventory for the production of 1 m^3 RA-SCC mixes

	Serial	0-0	50-0	100-0	50-50-1	50-50-2	50-50-3	50-75-1	50-75-2	50-75-3	100-75-1	100-75-2	100-75-3
Resource input	Limestone	1.63E+03	1.05E+03	4.70E+02	8.15E+02	8.15E+02	8.15E+02	6.98E+02	6.98E+02	6.98E+02	1.17E+02	1.17E+02	1.17E+02
	Coal	1.18E+03	1.18E+03	1.18E+03	5.92E+02	5.92E+02	5.92E+02	2.97E+02	2.97E+02	2.97E+02	2.96E+02	2.96E+02	2.96E+02
	Fossil oil	4.38E+02	4.37E+02	4.36E+02	2.20E+02	2.20E+02	2.20E+02	1.11E+02	1.11E+02	1.11E+02	1.11E+02	1.10E+02	1.10E+02
	Natural gas	1.51E+00	1.02E+00	5.32E-01	8.41E-01	8.40E-01	8.40E-01	7.50E-01	7.49E-01	7.49E-01	2.61E-01	2.60E-01	2.60E-01
Emission output	CO_2	4.92E+02	4.84E+02	4.75E+02	2.53E+02	2.53E+02	2.53E+02	1.37E+02	1.38E+02	1.38E+02	1.29E+02	1.29E+02	1.30E+02
	NO_x	1.42E+00	1.27E+00	1.12E+00	7.92E-01	7.97E-01	7.98E-01	5.52E-01	5.59E-01	5.61E-01	4.01E-01	4.08E-01	4.10E-01
	CH_4	3.50E-01	3.43E-01	3.41E-02	1.89E-01	1.89E-01	1.88E-01	1.12E-01	1.12E-01	1.11E-01	1.05E-01	1.04E-01	1.04E-01
	SO_2	5.91E-01	5.78E-01	5.65E-01	3.04E-01	3.05E-01	3.05E-01	1.67E-01	1.68E-01	1.68E-01	1.55E-01	1.55E-01	1.56E-01
	CO	1.28E+00	1.23E+00	1.18E+00	6.69E-01	6.70E-01	6.70E-01	3.87E-01	3.89E-01	3.90E-01	3.37E-01	3.39E-01	3.39E-01
	NMVOC	3.99E-01	3.00E-01	2.01E-01	2.16E-01	2.21E-01	2.22E-01	1.75E-01	1.82E-01	1.84E-01	7.55E-02	8.30E-02	8.45E-02
	N_2O	1.59E-03	1.63E-03	1.67E-03	1.01E-03	1.00E-03	9.99E-04	7.05E-04	6.87E-04	6.84E-04	7.45E-04	7.28E-04	7.25E-04
	NH_3	2.04E-02	2.04E-02	2.04E-02	1.02E-02	1.02E-02	1.02E-02	5.12E-03	5.12E-03	5.12E-03	5.11E-03	5.11E-03	5.11E-03
	PM_{10}	2.41E-02	1.53E-02	6.52E-03	1.38E-02	1.42E-02	1.43E-02	1.30E-02	1.37E-02	1.38E-02	4.29E-03	4.91E-03	5.04E-03

Table 5 Assumptions used in LCI calculations for the transportation modes and distances

Transportation details for	Modes	Distances (km)
Cement to concrete plant	Truck	50
NCA to concrete plant	Rail and truck	980 km by rail and 10 km by truck
Fine aggregates to concrete plant	Truck	40
RCA to concrete plant	Truck	20
Fly ash to concrete plant	Truck	20
Ground granulated blast furnace slag to concrete plant	Truck	200
Silica fume to concrete plant	Truck	200

6.2 Life Cycle Inventory (LCI) creation and analysis

In this study, the raw material transportation and production to the concrete plant and the production of concrete were calculated. Inputs are raw materials and energy as well as water depletion and materials consumed. The energy inputs to the system are electrical supply and fuels used, and the outputs are air emissions (i.e., CH_4, NOx, CO_2, CO, NMVOC, SO_2, N_2O, NH_3, and PM_{10}) produced at all stages.

The entire LCI for the production of 1 m^3 SCC is given in Table 4, which was collected mainly from opened literatures, monitoring analysis, interviews and site investigation with local manufacturers and suppliers. Furthermore, the database, which was provided by the China Centre of National Material Life Cycle Assessment (2010) at Beijing University of Technology and the Chinese Life Cycle Database (2012) provided by Integrated Knowledge for our Environment (IKE) at Sichuan University, was adopted. Generic inventory data of the main building materials and processes are presented in these databases.

Natural limestones were crushed and extracted from a quarry situated in Anhui Province and were transported to Nanjing by trucks. The transport distance is calculated to be about 1000 km. The locally available natural river sands were bought from a local supplier situated 50 km away from the concrete plant and transported by trucks. RCAs were produced from a demolished building located in Nanjing Jiangbei New Area. The crushed concrete elements were conveyed to the local recycling factory and processed into aggregate finished products after crushing. RCAs were transported to the concrete plant by trucks, and the transport distance is estimated to be less than 20 km. Cementitious binders are used for cement, FA, GGBS, and SF. Cement was purchased from a cement factory in Wuhu. FA, GGBS, and SF were all purchased from local suppliers. The inputs and outputs for the production and treatment of these SCMs are obtained according to Kurda *et al*. (2018). The assumptions of LCA input for the selected types of transportation modes and related distances are summarized in Table 5. In concrete plants, mixing, conveying, and pumping concrete ingredients and mixtures as well as molding concrete is carried out by using electricity and fuel. In this research, the energy depletion and related criteria air pollutants in related to the concrete production were obtained from the site investigation at the concrete factory.

6.3 Impact assessment

In the impact assessment stage, the LCI data is divided into several impact categories, which aim to classify, characterize, standardize, and quantify the impacts of ecosystems, human health, and the consumption of natural resources. This research adopted the CML baseline method to conduct the life cycle impact assessment (LCIA) analysis, which groups the life cycle inventory results into impact categories, according to themes such as climate change or ecotoxicity. The CML mid-point method is currently the most widely used and most reliable computational method in the field of LCA research, which commonly considers the effects of the global warming effect, the ozone layer and smog or chemical fog. In addition, the life cycle analysis software eBalance was adopted to facilitate the quantification of the impact categories and environmental comparisons.

Six environmental impact indicators, including global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), photochemical ozone production potential (POCP), human toxicity potential (HTP) and Abiotic Depletion Potential (ADP) are calculated in accordance with the LCA handbook in this study.

7. LCA results and discussions

Table 6 summarizes the calculated six environmental impact indicators (i.e., ADP, AP, GWP, HTP, EP, POCP) related to the production of 1 m^3 RA-SCC mixes, which are comparatively analyzed on the basis of per unit volume. Additionally, these impact categories are comparatively analyzed with respect to mechanical properties.

7.1 Comparison of LCA results for RA-SCC with various RCAs and SCMs

The calculated total GWP (kg of CO_2-eq/m^3) from the production of 1 m^3 SCC with various RCAs and SCMs, as well as the contributions to the GWP from major used concrete constituents, are further analyzed through Fig. 8. As shown in Fig. 8, concrete mixture 0-0 with 100% cement and 100% NCAs has the highest GWP. The key ingredient that generates the most considerable environmental impacts is cement. The cement production leads to the largest GHG emissions source, accounting for 72.2% to 93.2% of the total GWP. A few previous studies have also demonstrated that the main component of concrete, namely cement, accounts for the highest GHG emissions (87% to 96% total GWP). This is mainly due to the fuel combustion during cement production (Kurda *et al*. 2018). Thus, it is clear from Fig. 8 that GWP strongly decreased with the SCM content increasing (i.e., cement content decreasing). For example, when cement was 50% and 75% replaced by SCMs, GWP decreased 44.2% and 67.2%, respectively.

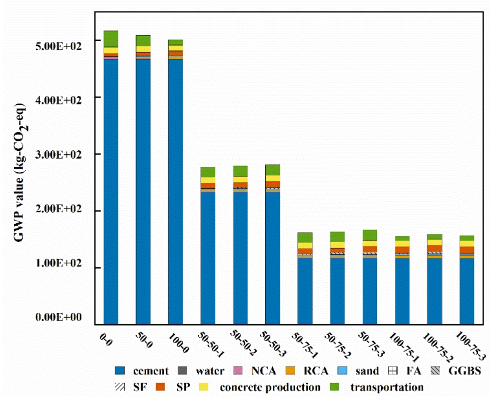

Fig. 8 Comparison of calculated GWP for RA-SCC production (kg of CO_2-eq/m^3 of concrete)

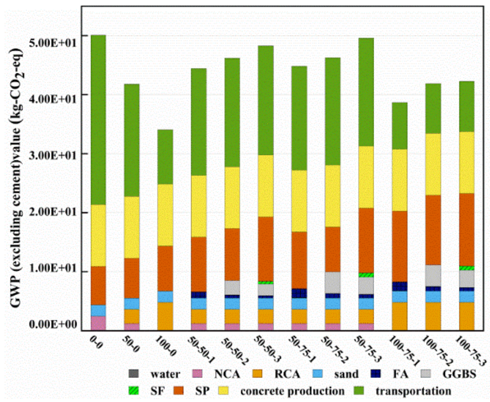

Fig. 9 Comparison of calculated GWP for the production of RA-SCC (excluding cement)

Similar results were also obtained by Teixeira *et al*. (2016).

It also can be seen from Fig. 8 that GWP declined slightly as RCA content increased. For example, the GWP decreased 3% when SCC mixtures blended with 100% RCAs. This is primarily attributed to the shorter transport distance of RCAs. The transport distance between the crushing factory and the concrete plant was considerably shorter than that between the concrete plant and the limestone quarry. A similar conclusion was proposed by Guo *et al*. (2018).

Fig. 9 further carefully investigates the sources of the major GWP emissions from other constituents (excluding cement). The delivery of all materials within the system boundary is the second greatest source of GWP, accounting

Table 6 Calculated six environmental impact categories

	0-0	50-0	100-0	50-50-1	50-50-2	50-50-3	50-75-1	50-75-2	50-75-3	100-75-1	100-75-2	100-75-3
GWP	5.17E+02	5.09E+02	5.01E+02	2.77E+02	2.77E+02	2.79E+02	1.60E+02	1.59E+02	1.62E+02	1.54E+02	1.54E+02	1.55E+02
AP	1.84E+00	1.73E+00	1.62E+00	1.13E+00	1.13E+00	1.15E+00	8.18E-01	7.98E-01	8.43E-01	7.30E-01	7.34E-01	7.41E-01
EP	2.05E-01	1.85E-01	1.66E-01	1.21E-01	1.21E-01	1.23E-01	8.81E-02	8.76E-02	9.02E-02	7.01E-02	7.09E-02	7.14E-02
HTP	1.91E+00	1.72E+00	1.54E+00	1.14E+00	1.14E+00	1.16E+00	8.39E-01	8.34E-01	8.61E-01	6.66E-01	6.75E-01	6.80E-01
POCP	3.16E-01	2.60E-01	2.05E-01	1.79E-01	1.81E-01	1.83E-01	1.37E-01	1.40E-01	1.43E-01	8.33E-02	8.72E-02	8.84E-02
ADP	6.90E-02	6.70E-02	6.52E-02	3.58E-02	3.58E-02	3.61E-02	2.01E-02	1.98E-02	2.03E-02	1.85E-02	1.85E-02	1.86E-02

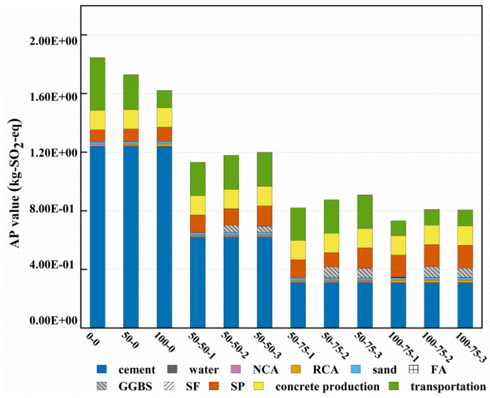

Fig. 10 Comparison of AP for RA-SCC production (kg of SO_2-eq/m^3 of concrete)

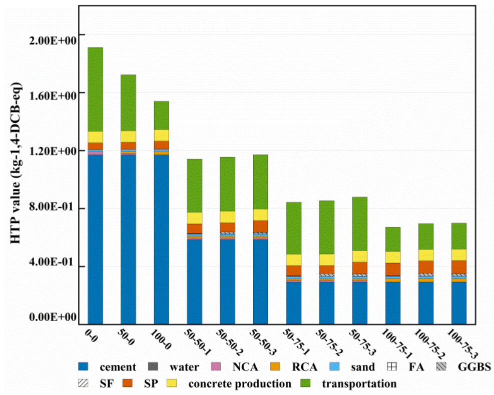

Fig. 12 Comparison of HTP for RA-SCC production (kg of 1, 4-DCB-eq/m^3 of concrete)

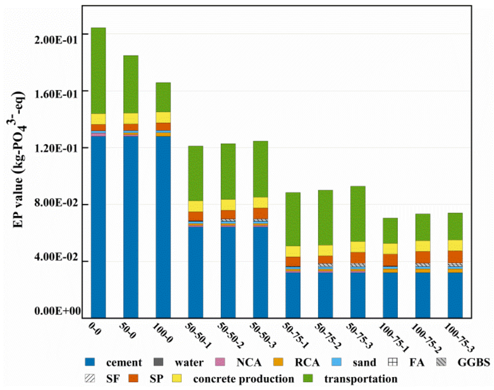

Fig. 11 Comparison of EP for RA-SCC production (kg of PO_4^{3-}-eq/m^3 of concrete)

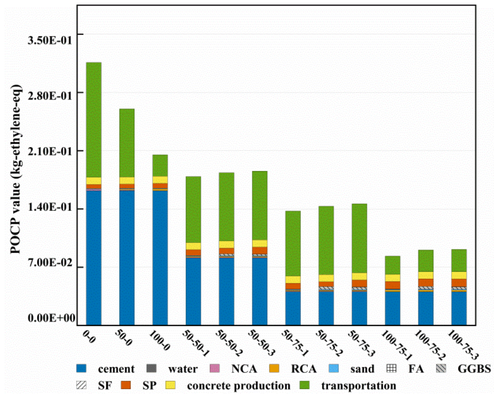

Fig. 13 Comparison of POCP for RA-SCC production (kg of C_2H_4-eq/m^3 of concrete)

for approximately 27.0%-57.4% of the total GWP (excluding cement), as shown in Fig. 9 Furthermore, it is apparent from Fig. 9 that GHG emissions generated from the production of RCAs is 96.7% higher than that from NCA production. This is consistent with the results proposed by Guo *et al.* (2018), which is primarily due to the electricity consumption during the crushing of recycled concrete aggregates is higher than that for natural aggregate extraction. However, Kurda *et al.* (2018) concluded that the GWP from the production of NCAs (0.029 kg-CO_2 eq/kg) is higher than that of RCAs, which is 0.005 kg-CO_2 eq/kg.

It is obvious from Figs. 10 and 11 that the proportion of changes of AP due to the incorporation of SCM and RCA is very close to that of EP. Thus, the same results concluded for AP could be applied to EP. Results reveal that the AP of NCA production is approximately 19% lower than that of RCA, and the EP of NCA production is also approximately 13.4% lower than that of RCA, which is attributed to the greater electricity consumption in the RCA crushing process. However, AP decreased to 6.0% and 19.0% when NCAs were 50% and 100% replaced by RCAs, respectively, which is due to the different transport distances. The transport distance between the limestone quarry and the concrete plant of NCAs (i.e., 1000 km) is remarkably longer than that of RCAs (20 km). In addition, the contribution of cement production and material transportation to the calculated EP and AP is significant, as shown in Fig. 10 and Fig. 11. Thus, the AP declined linearly with the replacement ratio of SCMs increased. For example, the AP decreased by about 29.5%-34.7% and 45.4%-52.3% when 50% and 75% of cement were replaced by SCMs, respectively. Similar conclusions were proposed by Kurda *et al.* (2018).

The calculated HTP (kg-1,4-DCB-eq/m^3 of concrete) of each SCC mix, as well as the contribution to the HTP by concrete constituents, are shown in Fig. 12. The results show that HTP decreased by about 10% and 19.4% when NCAs were 50% and 100% replaced with RCAs, respectively. In addition, HTP decreased by 31.4%-33.7% and 47.9%-51% when 50% and 75% of cement were replaced by SCMs, respectively, which is consistent with the conclusion proposed by AzariJafari *et al.* (2019). The same factors concerning the effect of incorporation of RCA and SCMs on the GWP of concrete mixes can be invoked for HTP. It can be seen from Fig. 12 that cement production results in the highest HTP, accounting for 34.0% to 76.0%.

Fig. 13 summarizes the calculated POCP (kg-C_2H_4-eq/m^3 of concrete) of each SCC. It is clear from Fig. 13 that POCP decreased when NCAs were replaced with RCAs. For example, POCP was reduced by about 35.1% and 28.1% when 100% and 50% NCAs were replaced with RCAs, respectively. This is mostly because of NCAs' longer transportation distances. It is obvious from Fig. 13 that transportation is a considerable contributor to the POCP (12.5% to 58.6%). In addition, POCP significantly

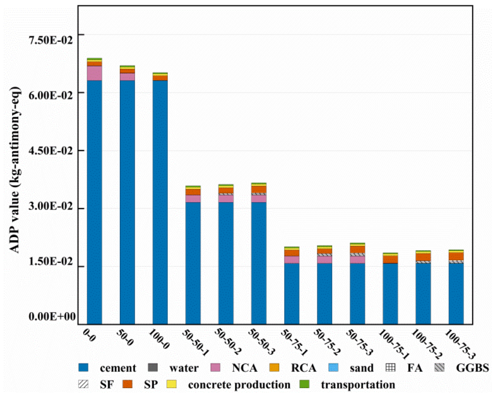

Fig. 14 Comparison of ADP for RA-SCC production (kg of Sb-eq/m^3 of concrete)

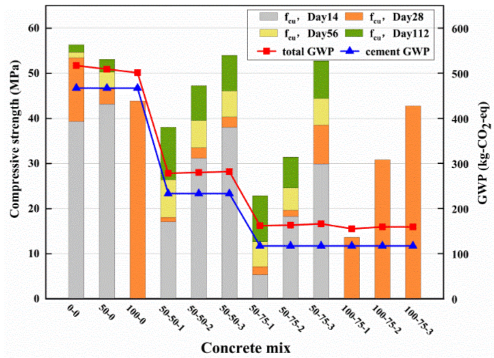

Fig. 15 Comparison of average compressive strength and GWP of RA-SCC mixes

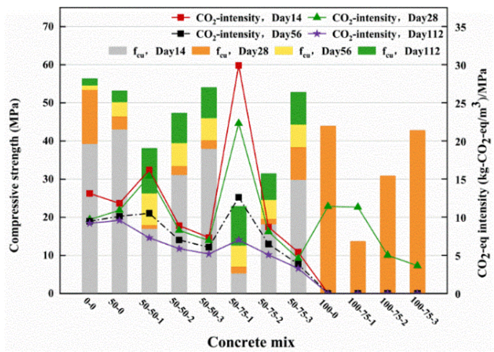

Fig. 16 Comparison of CO_2-eq intensities and compressive strength of RA-SCC mixes

decreased as cement was replaced with SCMs. POCP decreased about 31.2% and 46.9% when 50% and 75% of cement were replaced with SCMs, respectively. The same reasons with respect to the influence of SCM addition on the GWP of SCC mixes can be invoked for POCP. Similar conclusions were also proposed in previous investigations in terms of RCA concrete and FA concrete (Pradhan *et al.* 2019).

Fig. 14 illustrates the calculated ADP (kg-Sb-eq/m^3 of concrete) of each SCC mix with various RCAs and SCMs. As shown in Fig. 14, ADP slightly reduced as the RCA replacement ratio increased. For example, ADP decreased about 2.9% and 5.5% when 50% and 100% NCAs were replaced with RCAs, respectively. Furthermore, ADP significantly decreased as cement was replaced with SCMs. ADP decreased to 46.6% and 70% when 50% and 75% of cement was replaced with SCMs, respectively. Similar conclusions were also drawn by Kurda *et al.* (2018) for RCA concrete and FA concrete.

7.2 Comparison of LCA results with respect to mechanical properties

In order to quantify the relationship between mechanical properties and concrete environmental performance and how environmental performances are influenced by the variations in mechanical properties, LCA results are normalized and comparatively analyzed in relation to mechanical properties. The GWP development versus the compressive strength of SCC mixtures, as well as comparing the average strength of SCC mixes over curing time, is illustrated in Fig. 15. The red line reveals the calculated GWP from the production of SCC (kg CO_2-eq/m^3 of concrete) and the blue line reveals the cement contribution to the total calculated GWP. As shown in Fig. 15, the total calculated GWP has the same trends with the cement GWP. Furthermore, GWP declines significantly with the decreasing content of cement used, as shown in Fig. 15. At last, for a given SCM replacement ratio, the combination type of SCMs appears to have no effect on the total calculated GWP.

The CO_2-eq intensity, which is the ratio of calculated GWP to the compressive strength, was adopted to analyze the relationship between mechanical properties and calculated impact categories. The CO_2-eq intensity considers the compressive strength and the contribution of RA-SCC mixes to GWP emissions per unit strength and volume, thus is recognized as an innovative technique for the comparison of concrete mixes with various compressive strength in the search for an optimum volume of RCAs and Mineral additives, in order to seek the least environmental impacts (Gursel *et al.* 2016). The calculated CO_2-eq intensity per various-day compressive strength and unit volume versus compressive strength of sustainable SCC mixtures is illustrated in Fig. 16. The calculated CO_2-eq intensity slightly increased (i.e., 13% and 17.8%) when NCA was 50% and fully replaced with RCA, as shown in Fig. 16. In addition, the CO_2-eq intensity strongly decreased with the increasing of SCM content (i.e., cement content decreasing). At a specific compressive strength, the CO_2-eq intensities can be significantly reduced by replacing cement with SCMs, especially in later days (i.e., 56 and 112 days), as shown in Fig. 16. For instance, at a 112-day compressive strength of about 53.12 MPa, specimen 50-0 with 50% RCAs and 100% cement produces 9.6 kg CO_2-eq/MPa, while binary mixes 50-50-1 with 50% RCAs and 50% FA produces 7.3 kg CO_2-eq/MPa, and binary mixes 50-75-1 with 50% RCAs and 75% FA has a lower intensity of 7 kg CO_2-eq/MPa. A reduction in cement from 0% to 50% decreased the CO_2-eq intensity from 9.6 kg CO_2-eq/MPa to 7.3 kg CO_2-eq/MPa. At last, substituting cement with a combination type of GGBS, FA, or/and SF has further decreased the CO_2-eq intensities at all ages. For example, when the cement replacement ratio is 50%, the 112-day CO_2-eq intensities of ternary mixtures incorporating FA, GGBS, and quaternary mixtures incorporating FA, GGBS, and SF reduced by 19% and 29%, respectively, compared to that of SCC mixtures blended with only FA. When cement replacement ratio is 75%, the 112-day CO_2-eq intensities of ternary mixtures containing FA, GGBS and quaternary mixtures containing FA, GGBS and SF reduced by 26% and 53%, respectively, compared to that of SCC mixtures blended with only FA. Quaternary mixes 100-75-3 with 100% RCAs and 75% SCMs (30% FA + 30% GGBS + 15% SF) results in the lowest 112-day CO_2-eq intensity (3.3 kg CO_2-eq/MPa). Therefore, according to the results, it can be concluded that, for a given performance measure, such as strength, with mixture design advancement and combination type selection of SCMs (i.e., using a combination type of FA, GGBS, and SF), it is able to significantly decrease the CO_2-eq intensity of sustainable SCC mixtures incorporating RCAs and SCMs.

8. Conclusions

A sustainable SCC blended with high-volume RCAs and SCMs was prepared in this study. The mechanical properties in terms of compressive strength and elastic modulus of RA-SCC were determined and a microstructural study was implemented. Furthermore, using the LCA method, the environmental impacts of 1 m^3 of RA-SCC were considered for different environmental categories from "cradle to gate". The comparison of LCA results with respect to mechanical properties was implemented. Based on the test and LCA results and discussions, several conclusions can be obtained as follows:

1. The addition of RCAs declined the compressive strength and elastic modulus of SCC mixes. However, quaternary RA-SCC mixes containing FA, GGBS and SF attained similar compressive strength and elastic modulus in comparison with reference normal SCC, indicating that replacement cement with SCMs using a combination of FA, GGBS and SF can offset the adverse effect of RCAs and considerably enhance the mechanical properties of RA-SCC mixes.

2. The microstructural investigation reveals that the old and new ITZs and paste of quaternary RA-SCC mixes with FA, GGBS and SF are improved and strengthened, and a dense and stronger microstructure is produced after the addition of FA, GGBS and SF, which confirms the improvement of compressive strength and elastic modulus of RA-SCC mixes.

3. The production of RCAs resulted in slightly higher criteria air pollutants compared to NCAs, not only due to increased fuel consumption but also due to increased energy demand during the separation and recovery process of concrete waste. However, despite the relatively higher burden during the production stage of RCAs, RA-SCC still benefits compared to conventional concrete. When NCA is replaced entirely by RCA and accounts for 50%, six calculated impact categories (GWP, AP, HTP, EP, POCP, ADP) decreased, which is attributed to the longer transportation distance of NCA.

4. The environmental results show that cement has the greatest impact in all six environmental impact categories. Consequently, all the six impact categories significantly reduced with the cement content decreasing and SCM content increasing. Control normal SCC with 100% cement generated the highest GWP (i.e., 517 kg CO-eq/m^3), while SCC with 75% FA resulted in the lowest value of GWP, which is 154 kg CO_2-eq/m^3.

5. The introduction of a combination of FA, GGBS and SF remarkably reduced the CO_2-eq intensities per MPa. Thus, substituting cement with SCMs using a combination of FA, GGBS and SF for the production of RA-SCC mixes substantially decrease the environmental impacts without compromising compressive strength.

The results show that the incorporation of RCAs and SCMs to produce SCC using a combination of FA, GGBS and SF considerably enhance the mechanical and environmental performances of SCC. Furthermore, using a high content RCAs and SCMs leads to a remarkable reduction of natural resources consumption and waste products disposal, thus further resulting in a reduction on the environmental burdens and an improvement on the sustainability aspect of SCC mixes.

This study investigated six environmental impact categories i.e. GWP, AP, HTP, EP, POCP, ADP. The impacts of solid waste on the landfill capacity were not investigated in this study, which is of great important for future study. Therefore, future research should focus on developing specific indicators for the depletion of landfill space. Additionally, the technical pathways for producing RA-SCC vary across regions and countries. Thus, it is necessary to establish a dynamic life cycle inventory for RA-SCC by considering temporal, geographical, and further technological relevance. In addition to improving the mechanical properties and environmental performances, the incorporation of RCA and SCMs in concrete can also lead to economic benefits. In future research, to further demonstrate the sustainability of incorporating RCA and SCMs in concrete, an economic analysis should be conducted to make the assessment results of RA-SCC more scientific and reasonable. This will promote the application of RA-SCC in the concrete industry and reduce the environmental impact of concrete.

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