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The Effect of Fly Ash and Recycled Aggregate on the Strength and Carbon Emission Impact of FRCCs

Jong-Won Lee¹, Young-Il Jang², Wan-Shin Park², Hyun-Do Yun³ and Sun-Woo Kim^{2*}

Abstract

Concrete is the most widely used construction material in the world. In particular, cementitious composites that contain reinforced fibers have a relatively large amount of cement. Therefore, in this study, the target is to maintain at least 90% of the performance along with a reduction of CO₂ emissions from the material stage during fiber-reinforced cementitious composites (FRCCs) production by applying fly ash (FA) and recycled sand (RS). To calculate the amount of CO₂ emission at the stage of manufacturing the FRCCs, life cycle inventory database (LCI DB) were referenced from domestic and Japan. As the performance efficiency indicators, simple equations to evaluate the amount of CO₂ emission of FRCCs were then formulated as a function of the replacement ratio of FA and RS. And binder and CO₂ intensities were analyzed by FRCCs strength. Based on the results for the test, a mix of FA 25% and RS 25% of W/B 0.45, is considered most suitable in terms of performance of FRCCs and reduction of CO₂ emissions.

Keywords: fiber-reinforced cementitious composites, fly ash, recycled aggregate, performance, carbon dioxide emission

1 Introduction

Fiber-reinforced cementitious composites (FRCCs) can improve tensile strength and deformation capacity by adding about 2% of reinforcing fibers to compensate for brittle fracture characteristics of ordinary concrete. Furthermore, by forming an infinite number of micro-cracks through the bridging action of reinforcing fibers, excellent durability can be achieved, which means that the durability of the structure itself can be increased (Kim et al. 2010). However, FRCCs are high-energy consumption materials affiliated with mortar that require a relatively large amount of cement (944 kg of CO₂ is emitted in the production of 1 ton of cement based on the KOREA LCI DB) compared to ordinary concrete (Yoon

2007). Therefore, cementitious composites that contain reinforced fibers have a relatively large amount of cement. In particular, it is reported that CO₂ emissions of Strain Hardening Cement-Based Composite (SHCC) are 2.61 times that of ordinary concrete (Rister and Graves 2002).

The reduction of carbon dioxide (CO₂) is becoming a priority in the global cement industry's energy consumption reduction and greenhouse gas reduction (Park and Park 2008; Kim et al. 2011). As such, various efforts have been made to reduce CO₂ emissions and conserve natural resources around the world recently (Gartner 2004).

Green concrete research to reduce CO₂ emissions is actively utilizing blast furnace slag powder and fly ash (FA), which are industrial byproducts produced in a large volume of industries. Additionally, research on desulfurization gypsum and red mud are actively conducted domestically and internationally (Prasad et al. 2009; Ginés et al. 2009).

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Journal information: ISSN 1976-0485 / eISSN 2234-1315

In particular, while considerable developments have been made for geopolymer concretes, efforts have also been made to replace the cement-based binder in the current FRCCs with geopolymeric cement resulting in fiber-reinforced geopolymer composites, which are greener than the former. Although a great deal of important research has been performed on fiber-reinforced geopolymer composites, the field is still relatively young Shaikh (2014). It has been estimated that the manufacture of geopolymeric cement emits about 80% less CO₂ than the manufacture of ordinary portland cement (OPC) (Duxson et al. 2007; Xu and Van Deventer 2002) primarily because limestone does not need to be calcined to produce geopolymeric cement. FA based geopolymers have extremely low embodied energies. For a geopolymer based concrete (produced from FA and a soluble silica-like activator, and cured under mild heating), Tempest et al. (2009) estimated that 70% less energy is consumed when compared with OPC-based concrete of similar strength. Yang et al. (2007) showed the feasibility of creating green engineered cementitious composite (ECC) using a high volume of fly ash while maintaining tensile ductility. The fly ash was replaced up to 85% by weight of cement. The research results indicate that ECC with fly ash tends to reduce the crack width and improve the robustness of the tensile ductility, and also reduces the free drying shrinkage while slightly reducing the compressive strength after 28 days. Also, research on ECC using limestone powder as an inorganic binder has been actively conducted internationally (Hyun and Kim 2016; Tsivilis et al. 2003; Voglis et al. 2005).

Meanwhile, as part of the research for conservation of natural resources, research is underway to recycle construction waste into an alternative resource for natural aggregates (Park and Bae 2007; Lee et al. 2009). The use of recycled aggregates should be expanded in order to actively solve environmental destruction caused by the depletion of natural aggregates and the disposal of waste concrete, but they have not been widely used due to the lack of awareness on recycled aggregates and the lack of previous research on a recycled aggregate and recycled aggregate concrete. Thus, the use of recycled materials can reduce CO₂ emissions as well as provide a positive environmental impact of recycling construction waste and preserving natural resources (Cho and Chae 2015; Cho and Chae 2016). However, a previous investigation indicated that compared to the natural aggregate concrete (NAC) with same water to binder ratio (W/B), the recycled aggregate concrete (RAC) obviously degrade in compressive strength, splitting and flexural tensile, modulus of elasticity and frost resistance, while its drying shrinkage, creep, water absorption increased (Marinković et al. 2010).

Data that can easily evaluate CO₂ reduction due to recycled material substitution are very limited²¹. In particular, there are only a few studies regarding CO₂ reduction and using recycled aggregates (Yang et al. 2007) due to that the current research on FRCCs have mostly focused on improvement and identification of tensile performance of materials based on micromechanics (Prasad et al. 2009; Ginés et al. 2009). Marinković et al. (2010) reported that concrete recycling leads to CO₂ emission reductions only if the recycling plant is located near the building site. Authors argued that the recycling process is similar to crushed stone aggregate production and it is reasonable to assume that its energy demand is similar for both processes. However, due to the additional cement for compensating the low quality of coarse recycled aggregate, energy consumption and CO₂ emissions of RAC are highly dependent on the condition of the specific project, such as transportation, landfills and the LCI, which may be quite different from site to site. Akbarnezhad and Nadoushani (2015) The effects of various concrete recycling operations on CO₂ emissions were studied and showed that the level of CO₂ emissions can vary considerably depending on the recycling process adopted and the expected coarse recycled aggregate quality. Chowdhury et al. (2010) identified the limits for the transport requirements within which concrete recycling remains an attractive option in terms of energy and associated carbon emissions. A life cycle assessment (LCA) on both RAC and NAC was conducted by Turk et al. (2015) and found that the carbon emission of RAC was reduced to 96%; this number was, however, reported to be dependent on the transportation distance. Thus, the studies currently focus on CO₂ emissions of RAC rather than FRCCs.

Therefore, the objective of this study is to manufacture and develop FRCCs using recycled materials that maintain more than 90% performance of conventional FRCCs using Ordinary Portland Cement (OPC) for applying FRCCs using recycled materials such as FA and RS to structural members. In addition, an analysis was carried out on the CO₂ emissions and the recyclable material produced during the manufacture of FRCCs, by analyzing the compressive, flexural and tensile strength of FRCCs according to CO₂ emissions. Furthermore, this will present basic data for developing optimal FRCCs that can provide not only sustainability, economic feasibility but also environmental load reduction performance.

2 Materials and Experiment Method

2.1 Material Used

The material foreground (Fig. 1) and physical, chemical and mechanical used in this study are shown in Tables 1, 2 and 3, respectively. The cement used was ordinary

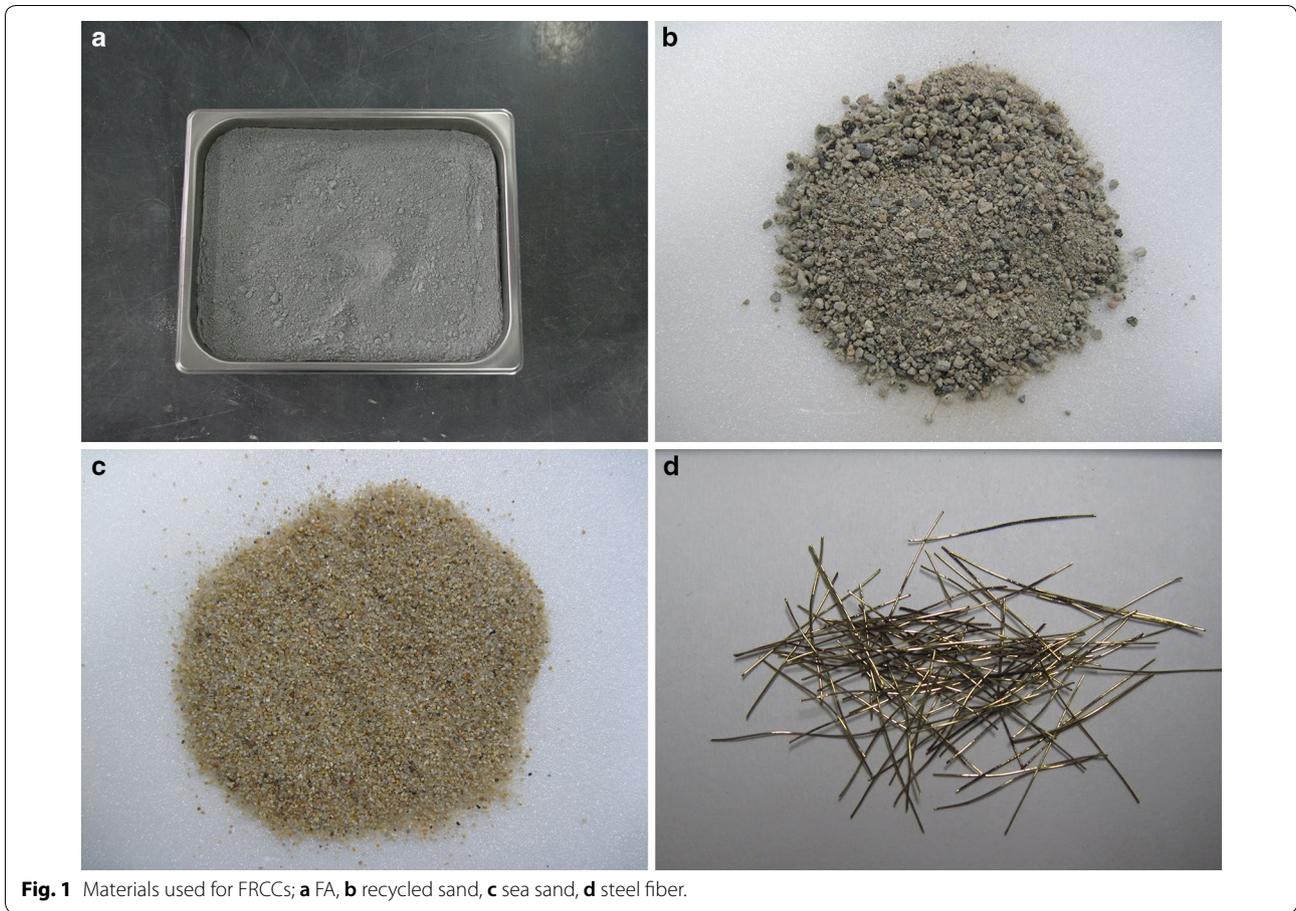


Table 1 Physical properties of FA.

Density (g/cm ³)	Blaine fineness (cm ² /g)	Chemical properties (%)					
		SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃
2.11	3990	21.1	4.65	3.14	62.8	2.81	2.1

Table 2 Physical properties of sand.

Item	Density (g/cm ³)	Water absorption (%)
Sea sand	2.59	0.76
Recycled sand	2.44	4.32

Table 3 Physical properties of micro steel fiber.

Density (g/cm ³)	Length (mm)	Diameter (μm)	Aspect ratio	Tensile strength (MPa)	Modulus of elasticity (GPa)
7.85	12-14	180-230	52-77	2580	206

Portland cement with a density of 3.14 g/cm³ produced by Korea company A as defined in ASTM C150 (2003), and the FA was F grade, a by-product of Korea B thermal power plant with a density of 2.11 g/cm³. The fine aggregate used was Jumunjin sea sand, manufactured in Jumunjin-eup, Gangwon-do, and specified compressive strength (f_{ck}) of original concrete used for manufacturing RS in this study was 18 MPa. The pieces of concrete were crushed and sieved into required aggregate sizes using a jaw-crusher by following Korea Standard sieves. Micro-steel fiber (MSF) from Japanese company K was used as reinforcing fiber, and polycarboxylic acid-based water reducing agent which improves workability and unit water quantity reduction by dispersing cement and taking in fine air was used as an admixture.

2.2 Experiment Method

In this study, to identify the mechanical characteristics of cement composites reinforced with MSF by replacement of recycled materials, the water-binder ratio ($W/B = 0.35, 0.45$) was determined by preliminary experiment, and the MSF was determined as 1% binder volume ratio. The replacement rates of the recycled materials were set at 25% and 50%, and the mixing conditions are shown in Table 4. A total of 240 specimens were prepared, 20 specimens for each mix, including

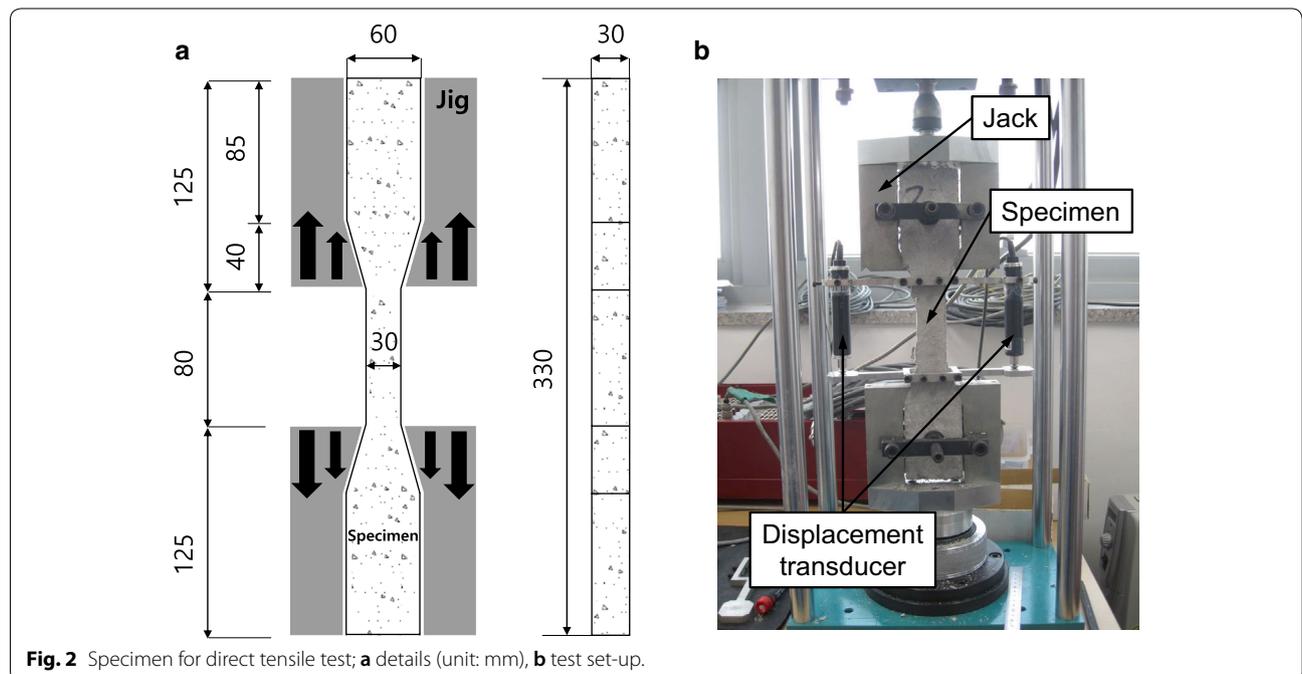
10 specimens to test flexural and compressive strength and 10 specimens to test direct tensile strength. Compressive and flexural strength specimens were manufactured and tested in accordance with ISO 679 (2009) by casting them in a $40 \times 40 \times 160$ (mm) mold. For direct tensile strength tests, a dumbbell type was fabricated as shown in Fig. 2a, and a direct tensile strength tester was used to quantitatively evaluate the tensile behavior characteristics, as shown in Fig. 2b. The specimens were removed from the form 1 day after casting

Table 4 Mix proportions of FRCCs.

Specimen type	Mix no.	W/B	Unit weight(kg/m ³) ¹					SP ^e	
			Water	Cement	FA ^a	SS ^b	RS ^c		MSF ^d
Mortar	Plain	0.35	303	866	–	1039	–	–	2.34
FRCCs	OPC100		302	863	–	1036	–	21.59	4.91
	FA25RS25		290	622	207	747	249	23.27	4.72
	FA25RS50		289	618	206	495	495	23.13	4.69
	FA50RS25		281	401	401	723	241	24.97	4.56
	FA50RS50		279	399	399	479	479	24.83	4.54
Mortar	Plain	0.45	327	727	–	1091	–	–	–
FRCCs	OPC100		326	725	–	1088	–	18.14	2.18
	FA25RS25		315	525	175	788	263	19.65	2.10
	FA25RS50		313	522	174	522	522	19.53	2.09
	FA50RS25		307	341	341	767	256	21.19	2.04
	FA50RS50		305	339	339	508	508	21.06	2.03

^a Fly ash, ^bSea sand, ^cRecycled sand, ^dMicro steel fiber, ^eSuper plasticizer.

¹ Air contents for calculating mix proportion was assumed to 2.0%.



and water cured at 20 ± 2 °C for 28 days in a constant-temperature water bath.

3 Assessment Procedure for CO₂

3.1 System Boundary

LCA system of a typical structure consists of production and transportation of component materials, construction of the structure, life cycle and disposal, etc. (Yang and Moon 2012). CO₂ emissions from LCA should consider all of the above factors, but the contribution to LCA on recycled materials which are addressed as variables in this study is concentrated in the production part of the component materials. In addition, system boundaries were set to the raw material production stage in this study, in other words, the material stage, of each component material in order to analyze the efficiency of strength versus environmental load according to each mix. At this time, because cementitious composites are ordered and produced in units of 1 m³, the functional unit for CO₂ evaluation in the FRCC mixing stage was set to 1 m³.

3.2 LCI Data Base

The life cycle inventory data base (LCI DB) for performing CO₂ evaluation of FRCCs must include the input and output factors required for each activity involved in the production of each material, the FRCCs production stage. FRCCs List data collected from component materials, transportation, and production activities are different in each country depending on the differences in temperature, energy sources, and natural resources, so it is advisable to use data available in your own country (Jung and Yang 2015). Therefore, in this study, the national LCI DB of Korea and LCI DB (KEITI 2017) of the Ministry of Land, Infrastructure, and Transport (2015) were investigated, and the CO₂ emission factor of the raw material production phase of FRCCs mix materials is summarized in Table 5. However, as there is no LCI DB in Korea and other countries for Jumunjin sea sand and MSF, reference has been made from prior research papers (Kim et al.

2015). And for SP, data lists presented by the Japan Society of Civil Engineers used (Sakai and Kawai 2006).

3.3 CO₂ Evaluation Procedure

The total amount of CO₂ emitted (C_d) from the system, from the outlet of each material of FRCCs functional units to the stage before FRCCs construction can be calculated by the following Eqs. (1) and (2).

$$C_d = CO_{2-M} + CO_{2-T} + CO_{2-P} \quad (1)$$

In this regard, CO_{2-M} is the CO₂ emissions from the material stage, including cement, each admixture, aggregate, water and admixture (water reducing agent), CO_{2-T} is the CO₂ emissions from each material and the transportation stage of the produced FRCCs, and CO_{2-P} is the CO₂ emissions at the production stage, calculated from the power consumed to mix the FRCCs.

$$CO_{2-M} = \sum_{i=1}^n (W_i \times CO_{2(i)-LCI}) \quad (2)$$

where, i is the individual materials used for the production of FRCCs, n is the number of these materials, W_i and $CO_{2(i)-LCI}$ are the unit mass (kg/m³) and CO₂ emission factor (CO₂-kg/kg) of the individual materials i (Cho and Chae 2015).

The application of FRCCs' CO₂ emission reduction technology can be evaluated by material, transportation, and manufacturing stages. At the material stage, reduction performance of CO₂ emissions can be evaluated by substituting recycled materials instead of cement and the transportation stage is divided into short distance procurement and energy reduction. The manufacturing stage can be divided into new and renewable energy application and manufacturing facilities (Kim and Tae 2010). In this study, because the environmental load reduction performance of FRCCs by using recycled materials is evaluated, CO₂ emissions were only calculated up to the material stage, and the transportation and manufacturing stages were excluded.

Table 5 LCI DB used for assessing CO₂ emissions of FRCCs.

Material	CO ₂ inventory	References	URL
OPC	9.44E-01 kg/kg	Korea LCI DB (2017)	http://www.epd.or.kr/lci/lcidb.do
FA	3.55E-03 kg/kg	MOLIT ^a LCI DB (2015)	https://www.gbc.re.kr/index.do
Water	1.96E-04 kg/kg	Korea LCI DB (2017)	http://www.epd.or.kr/lci/lcidb.do
Sea sand	4.42E+00 kg/m ³	Korea LCI DB (2017)	http://www.epd.or.kr/lci/lcidb.do
Recycled sand	2.94E-02 kg/kg	MOLIT ^a LCI DB (2015)	https://www.gbc.re.kr/index.do
MSF	1.60E-00 kg/kg	Kim et al. (2015)	-

^a Ministry of land, infrastructure and transport (Rep. of Korea).

Table 6 shows an example of FRCC-2 (W/B = 35%) calculated by Eq. (2), which is the equation for estimating CO₂ emissions at the material level of FRCCs. Column A is the unit mass of each material, with information related to the FRCCs mix, and column B is the amount of CO₂ provided by the LCI database of each material, so the CO₂ emissions from the production of component materials from FRCCs production were calculated by the times of columns A and B, respectively. At this time, the amount of water used for each mix was additionally calculated by considering the water absorption rate of the recycled aggregate (4.32%) as compared with that of the natural aggregate.

3.4 Binder Intensity and CO₂ Intensity

As shown in Table 6, the OPC accounts for the largest proportion of CO₂ emissions associated with the materials used to make FRCCs. Therefore, in order to reduce the CO₂ emissions of FRCCs, it is necessary to reduce the usage of OPC which is very important in terms of the environmental impact of binders. For this reason, Yang et al. (2013), Damineli et al. (2010) and Aïtcin (2000) conducted research on the efficient use of binders to reduce CO₂ emissions. In particular, Damineli et al. suggests that the environmental efficiency of concrete needs to be defined in terms of total binder consumption regarding the required strength and life cycle. On the other hand, the increase in the strength of the concrete can reduce the cross-sectional size of the structural member, so that the CO₂ reduction effect can be expected by reducing the amount of concrete. Therefore, the amount of binder and the corresponding amount of CO₂ required for expressing unit strength (1 MPa) needs to be evaluated. In short, the binder index (*B_i*) measures the amount of binder (kg/m³) necessary to deliver 1 MPa of mechanical strength, and consequently express the efficiency of using

binder materials. The CO₂ index (*C_i*) allows estimating the global warming potential of concrete formulations. It is considered that the combination of low *B_i* and *C_i* is an important index to improve the environmental load reduction performance of FRCCs. In this study, the environmental performance of FRCCs binders according to the replacement of FA and RS was evaluated by using the *B_i* and *C_i* presented by Damineli et al. (2010).

$$B_i = B/f \tag{3}$$

$$C_i = C/f \tag{4}$$

where *B* is the amount of binder (kg/m³) for FRCCs functional unit (1 m³); *C* is the total CO₂ emission (kg/m³) for the functional unit (1 m³); *f* is the strength (MPa) for the respective mechanical characteristics such as compressive, flexural and direct tensile strength.

4 Results and Discussion

4.1 Mechanical Properties Assessment of FRCCs

Table 7 shows the mean values and standard deviations of the compressive, flexural and direct tensile strengths of 28 days according to the replacement rate of recycled materials when mixed with W/B 0.35 and W/B 0.45. As the W/B decreased, the compressive, flexural and direct tensile strengths of each mix increased, and the flexural load–displacement curves did not show unusual features according to the recycled materials. The strength of FA25RS25 and FA25RS50, and FA50RS25 and FA50RS50 of W/B 0.35 and W/B 0.45 showed a slight decrease or increase as the replacement ratio of RS increased. Therefore, it is considered that the replacement ratio of RS relatively slightly affects to strength. In the mix designs of FA25RS25 and FA50RS25 and FA25RS50 and FA50RS50 at the same W/B, the flexural, compressive, and direct tensile strength were lower in the 50% of FA replacement ratio compared to 25% of FA replacement ratio. As the FA replacement ratio increased, it was determined that the strength decreased slightly due to FA which delayed early-age strength development (Kim et al. 2010).

4.2 CO₂ Emission Assessment of FRCCs

In this study, the target is to maintain at least 90% of the performance of OPC100 along with a reduction in CO₂ emission from the material stage during FRCCs production by applying FA, RS, etc. CO₂ emissions are affected by the type of binder and the higher the W/B, the lower the CO₂ emission (Fig. 3). In general, the compressive strength of concrete tends to increase as the W/B decreases, and a large amount of binder is required to exhibit high compressive strength. As a result, as the W/B is decreased from 0.45 to 0.35, the amount of the binder

Table 6 Example of CO₂ assessment for FA25RS25 (W/B = 0.35).

Material	A ^a (kg/m ³)	B ^b (kg/kg)	A · B ^c (kg/m ³)
OPC	622	0.944	587.168
FA	207	0.00,355	0.73,485
Water	301	0.000,196	0.058,996
Sea sand	747	0.00,171	1.27,737
Recycled fine aggregate	249	0.0294	7.3206
MSF	23.27	1.6	37.232
SP	4.72	0.25	1.18
Total			635.0

^a The unit mass of each material, ^bthe amount of CO₂ provided by the LCI database of each material, ^cCO₂ emissions from the production of component materials.

Table 7 Compressive, flexural and tensile strengths of 28-day.

Mix no.	W/B	Compressive strength (MPa)	Specimen performance (%)	Flexural strength (MPa)	Specimen performance (%)	Tensile strength (MPa)	Specimen performance (%)
Plain	0.35	47.21 (±0.32)	–	6.22 (±0.22)	–	0.70 (±0.16)	–
OPC100		67.23 (±0.50)	100	7.18 (±0.16)	100	1.69 (±0.17)	100
FA25RS25		60.56 (±0.19)	90.1 (–9.9)	6.08 (±0.13)	84.7 (–15.3)	1.63 (±0.22)	96.4 (–3.6)
FA25RS50		51.16 (±0.40)	76.1 (–23.9)	5.92 (±0.12)	82.5 (–17.5)	1.49 (±0.16)	88.2 (–11.8)
FA50RS25		44.82 (±0.14)	66.7 (–33.3)	5.68 (±0.17)	79.1 (–20.9)	1.39 (±0.29)	82.2 (–17.8)
FA50RS50		47.20 (±0.65)	70.2 (–29.8)	5.71 (±0.27)	79.5 (–20.5)	1.41 (±0.24)	83.4 (–16.6)
Plain	0.45	43.53 (±0.32)	–	4.55 (±0.20)	–	0.95 (±0.28)	–
OPC100		45.63 (±0.35)	100	5.02 (±0.04)	100	1.32 (±0.23)	100
FA25RS25		43.38 (±0.29)	95.1 (–4.9)	5.28 (±0.23)	105.2 (+5.2)	1.39 (±0.14)	105.3 (+5.3)
FA25RS50		43.24 (±0.40)	94.8 (–5.2)	5.52 (±0.24)	110.0 (+10.0)	1.19 (±0.14)	90.2 (–9.8)
FA50RS25		31.46 (±0.49)	68.9 (–31.1)	4.87 (±0.23)	97.0 (–3.0)	1.04 (±0.11)	78.8 (–21.2)
FA50RS50		34.38 (±0.28)	75.3 (–24.7)	4.51 (±0.09)	89.8 (–10.2)	1.08 (±0.17)	81.8 (–18.2)

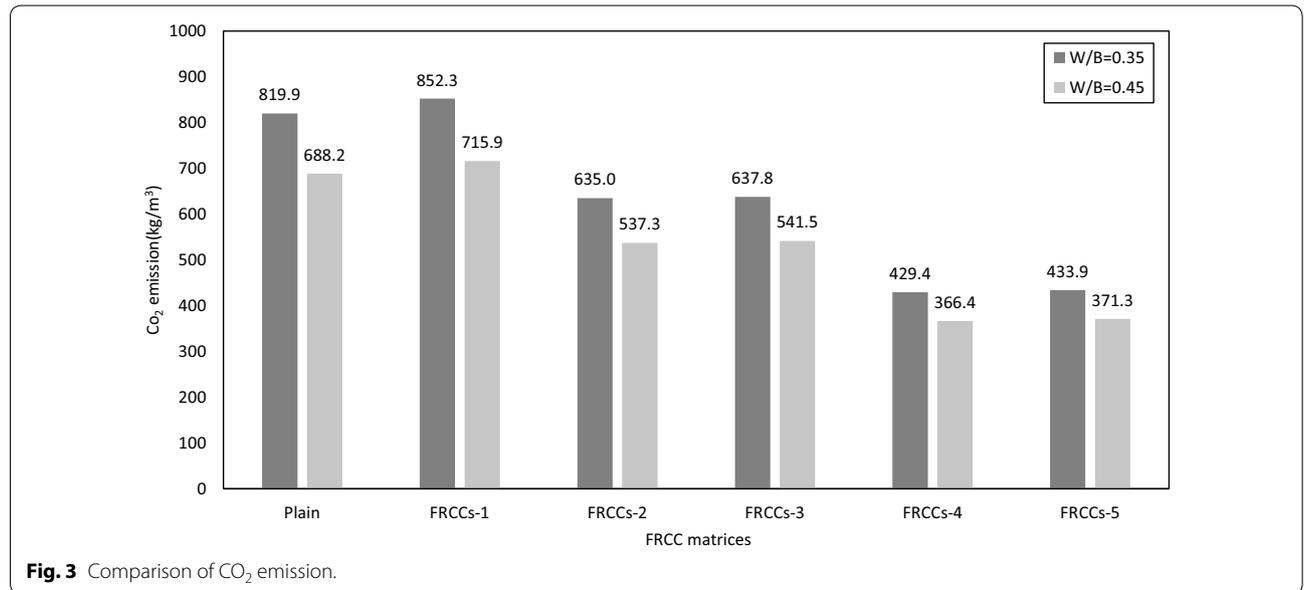


Fig. 3 Comparison of CO₂ emission.

consumed increases relatively, so that all mixes of the W/B 0.35 showed a difference of 14.4–16.1% compared to the W/B 0.45, and the CO₂ emission was increased.

In each W/B mix design, 819.9, 688.2 kg/m³ of CO₂ was emitted from OPC100, and from the results of analyzing the CO₂ emissions according to the replacement rate of recycled materials, the amount of CO₂ emission at W/B 0.35 was reduced to 25.5%, 25.2%, 49.6%, and 49.1% comparing OPC100 with FA25RS25, FA25RS50, FA50RS25, and FA50RS50 respectively. Comparison of FA25RS25 and FA25RS50 with 25% FA replaced showed that the difference of CO₂ emission caused by RS increased by 0.4% in FA25RS50. For FA50RS25 and

FA50RS50 which were replaced with 50% FA, the difference in CO₂ emissions caused by RS increased by 1.0% in FA50RS50. Meanwhile, for FA25RS25 and FA50RS25 with a 25% RS replacement ratio, the CO₂ emissions decreased by 32.4% in FA50RS25 as the FA replacement ratio increased, and for FA25RS50 and FA50RS50 with a 50% RS replacement ratio, the CO₂ emissions of FA50RS50 decreased by 32.0%.

At W/B 0.45, the CO₂ emissions reduced for FA25RS25, FA25RS50, FA50RS25, and FA50RS50 compared to OPC100 were 24.8%, 24.2%, 48.7%, and 48.0%, respectively. Comparison of FA25RS25 and FA25RS50 replaced with 25% FA, showed that the difference in

CO₂ emissions caused by RS increased by 0.8% in FA25RS50.

For FA50RS25 and FA50RS50 replaced with 50% FA, the difference in CO₂ emissions due to RS showed that FA50RS50 increased by 1.3%. Meanwhile, for FA25RS25 and FA50RS25 with a 25% RS replacement ratio, the CO₂ emissions decreased by 31.8% in FA50RS25 as the FA replacement ratio increased, and for FA25RS50 and FA50RS50 with a 50% RS replacement ratio, the CO₂ emissions decreased by 31.4% in FA50RS50.

As a result of analyzing the CO₂ emissions of FRCCs using recycling materials, CO₂ emissions decreased as the FA replacement rate increased. However, as the replacement ratio of RS increased, CO₂ emissions for each mix of W/B 0.35 increased about 0.4% and 1.0%, respectively, and for W/B 0.45 they increased about 0.8% and 1.3%, respectively. The higher the W/B, a lower amount of binder is required, but the amount of fine aggregate increases relatively. In addition, the analysis showed that the CO₂ emissions increased as the RS replacement ratio increased. The CO₂ emission factor of the recycled aggregate in the Korea LCI DB is calculated by considering the construction waste transportation stage and the manufacturing stages which are grinding and crushing processes. In particular, because there is a screening process of below 5 mm added to the RS used in FRCCs, it is considered that the CO₂ emission factor is higher than that of Jumunjin sea sand. However, it is advisable in terms of reducing construction waste and recycling as a natural aggregate alternative resource, and it should be actively considered in the future development of resource recycling type materials. Meanwhile, regardless of W/B, Plain CO₂ emissions were reduced by 1.6% compared to OPC100. It is

considered that the CO₂ emission decreased because Plain does not contain MSF.

4.3 Binder Intensity

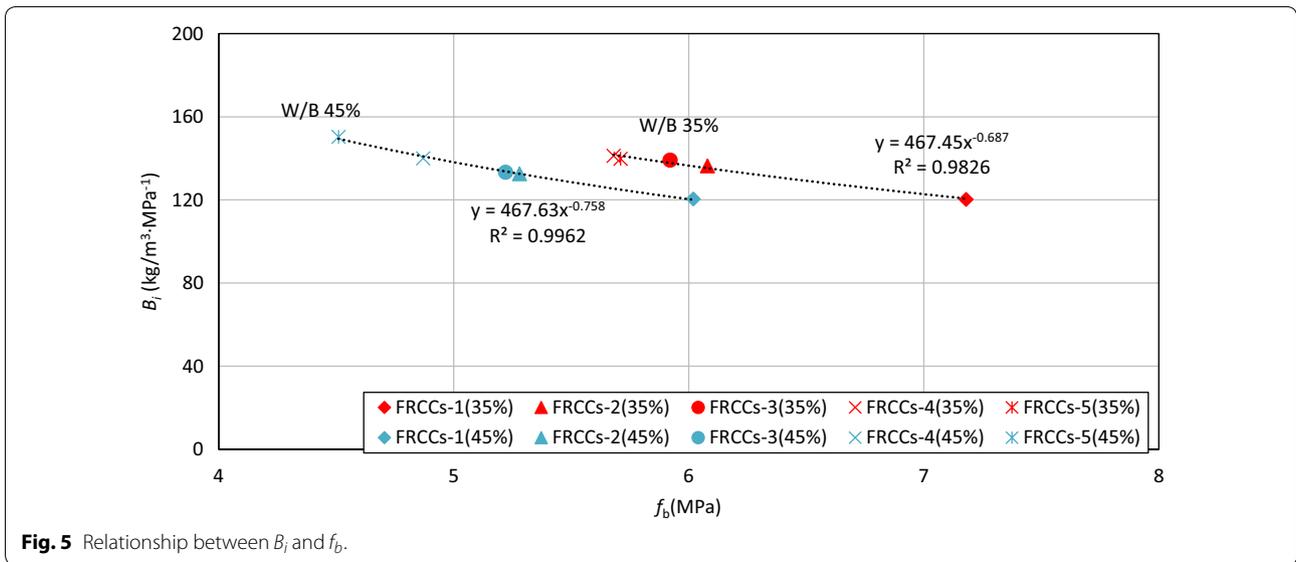
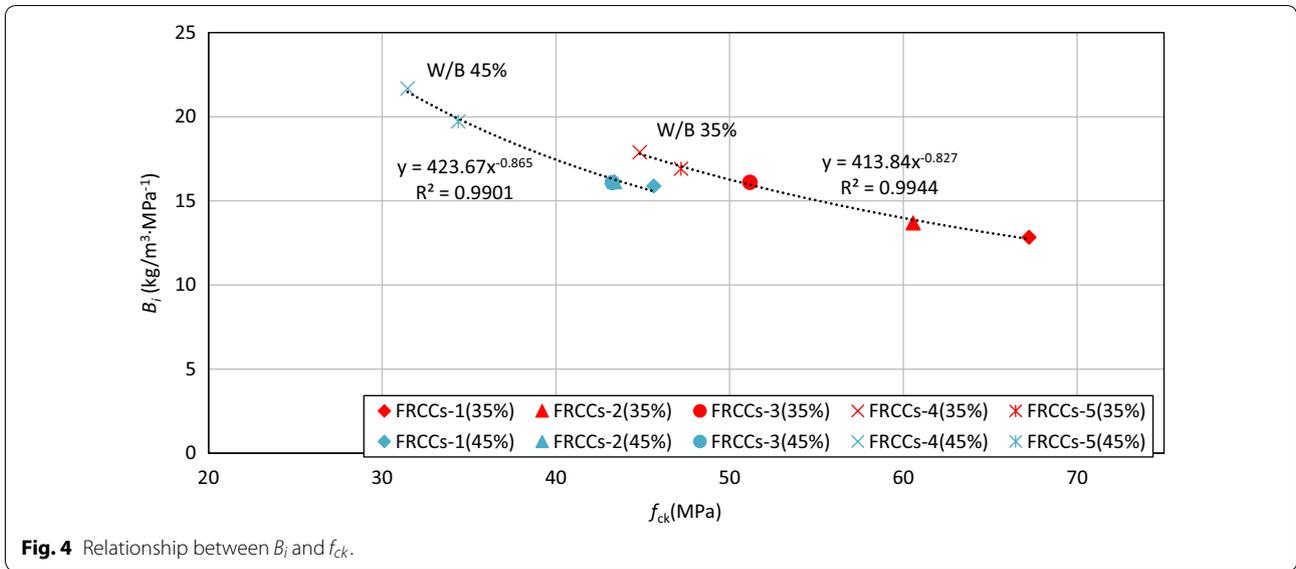
In this study, the experimental results of the mechanical characteristics according to each mix are summarized and the relationship between compression, bending and direct tensile strength according to each experiment. At this time, the Plain without MSF did not show tensile characteristics of FRCCs and therefore was excluded from the analysis. Additionally, the relationship between B_i according to compression, flexural and direct tensile strength is shown in Table 8.

For compressive strength, B_i tends to decrease in the order of FA 50% > FA 25% > OPC 100% (Fig. 4). This indicates that the amount of binder to reach unit compression strength (1 MPa) is higher than that of OPC. In the case of FA25RS25 and FA25RS50 replaced with 25% FA at W/B 0.35, compared with OPC100, the compressive strength decreased to 60.13 MPa and 51.16 MPa, respectively, and the increase in b_i was noticeable due to the decrease in strength according to the RS. Meanwhile, the mix of FA50RS25 and 5 replaced by 25% and 50% of RSs was not much difference from FA 50%, so the B_i was similar. For W/B 0.45, it was confirmed that B_i was varied according to the replacement ratio of RS at 50% replacement ratio of FA. It was also found that B_i according to the replacement ratio of FA increased more than W/B 0.35.

The flexural strengths of W/B 0.35 and 0.45 were similar to those of compressive strength (Fig. 5). It is considered that this is due to the compressive strength higher than W/B 0.45 due to the relatively low W/B, rather than the influence of fiber bridging action of

Table 8 B_i and C_i of compressive, flexural and tensile strengths.

Mix no.	W/B	Compressive strength		Flexural strength		Tensile strength	
		B_i	C_i	B_i	C_i	B_i	C_i
Plain	0.35	18.34	20.05	139.23	152.22	1237.14	1352.57
OPC100		12.84	14.22	120.19	133.11	510.65	565.51
FA25RS25		13.69	12.06	136.35	120.10	508.59	447.97
FA25RS50		16.11	14.43	139.19	124.70	553.02	495.45
FA50RS25		17.89	11.06	141.20	87.29	576.98	356.69
FA50RS50		16.91	10.68	139.75	88.28	565.96	357.52
Plain	0.45	16.70	21.75	159.78	208.06	765.26	996.48
OPC100		15.89	20.94	120.43	190.35	549.24	723.92
FA25RS25		16.14	16.87	132.58	138.61	503.60	526.52
FA25RS50		16.10	17.17	133.33	134.46	584.87	623.71
FA50RS25		21.68	15.82	140.04	102.20	655.77	478.57
FA50RS50		19.72	14.78	150.33	112.65	627.78	470.42



the mixed MSF. FA25RS25 and FA25RS50 showed a tendency to decrease in flexural strength as the RS replacement ratio increased, but the difference was insignificant.

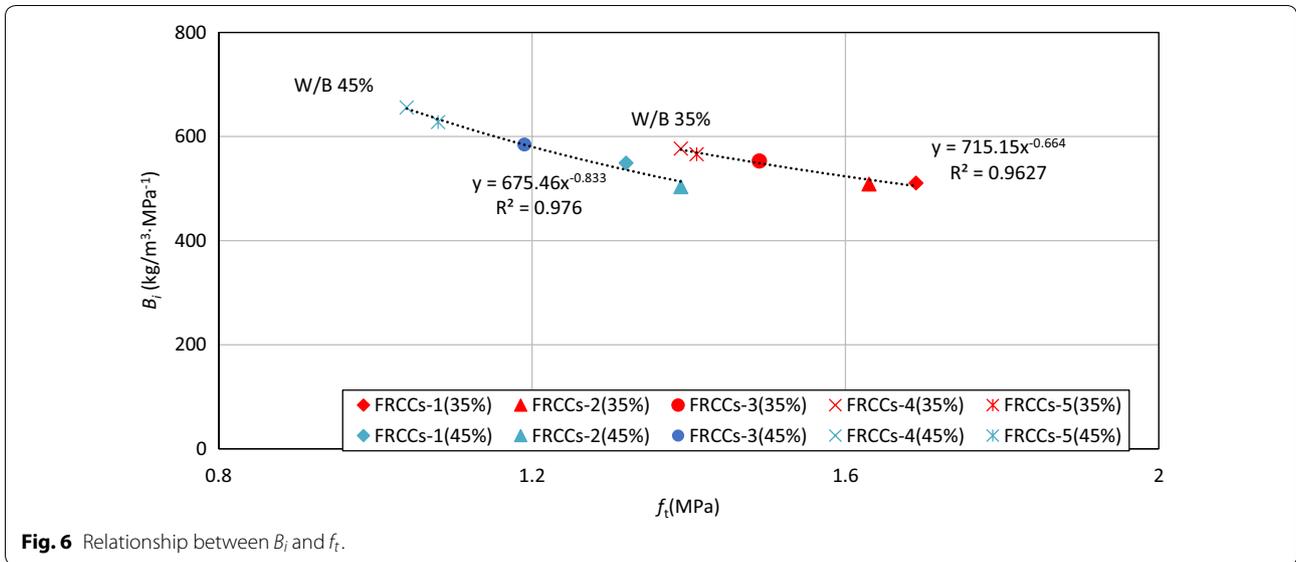
In the case of direct tensile strength, the replacement ratio of 25% of FA was measured to have high strength, showing a lower B_i compared to strength (Fig. 6). However, as the replacement ratio of RS increased, the direct tensile strength decreased, thus B_i increased. Meanwhile, the mix of 50% replacement of FA, the direct tensile strength tended to increase as the replacement ratio of RS increased, but the difference was not significant and B_i also showed no difference.

Therefore, when considering the direct tensile strength alone, the best mix was FA50RS25 mixed with 25% FA and 25% RS.

As a result, a relatively high correlation coefficient (R^2) between each strength data and the B_i is obtained. Hence, the relationship between the binder and strengths is helpful in designing a sustainable FRCCs.

4.4 CO₂ Intensity

The experimental results of the mechanical characteristics of each mix and the relationship between the non-dimensional value of the strength and C_i for each experiment are summarized in this study. At this time,

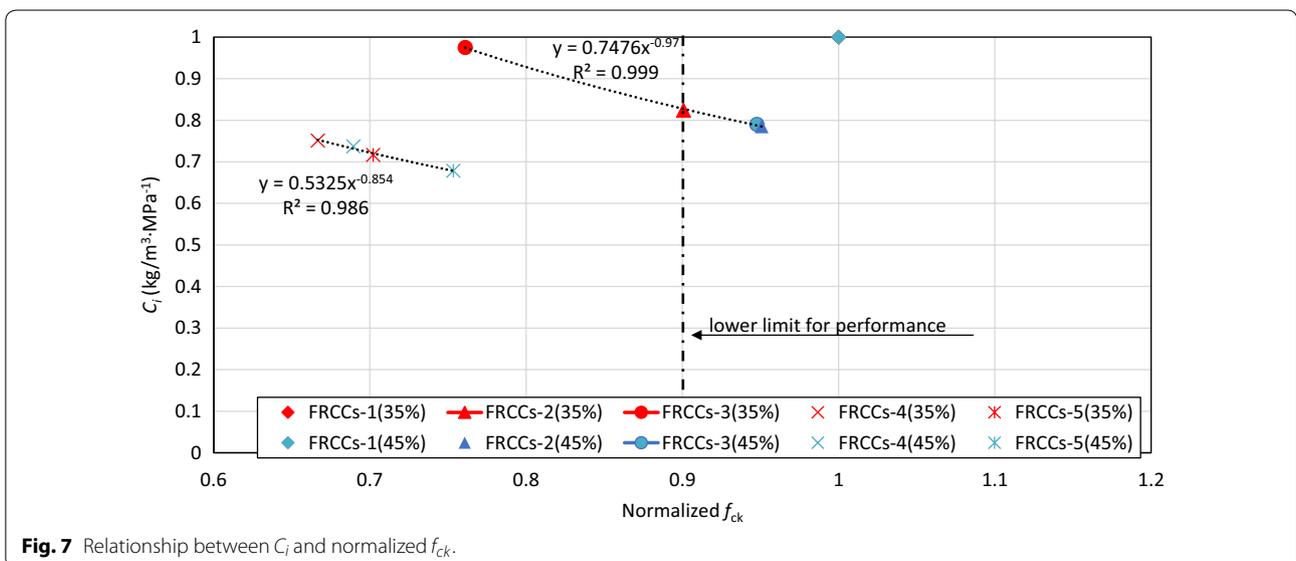


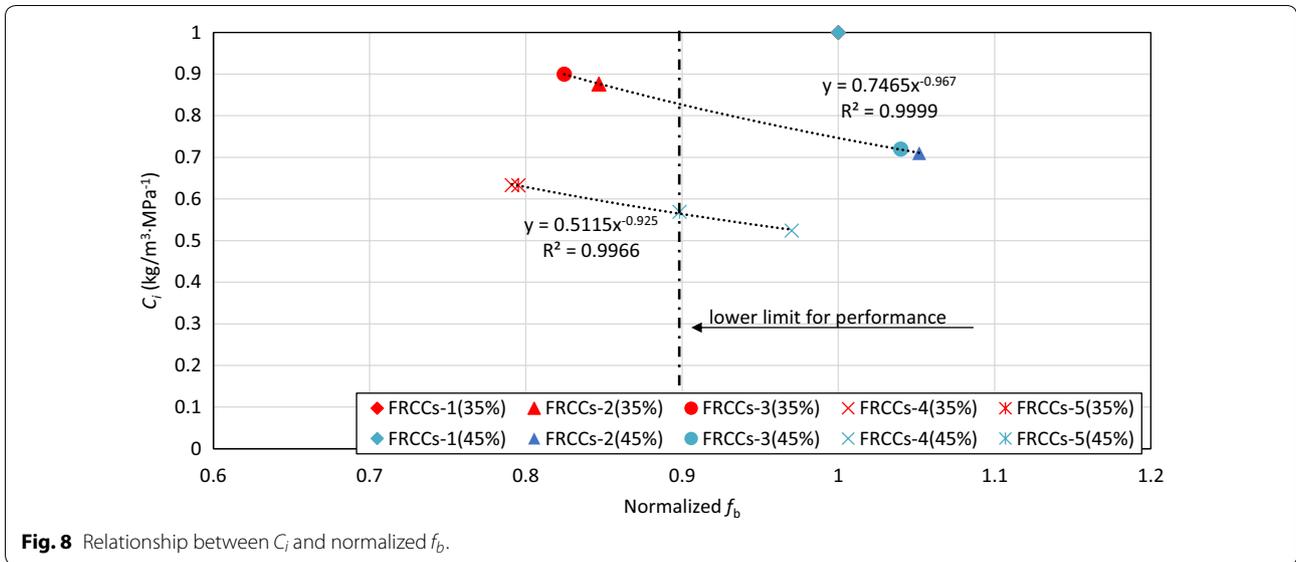
the Plain without MSF did not show tensile characteristics of FRCCs and therefore was excluded from the analysis. Additionally, the relationship between C_i according to compression, flexural and direct tensile strength is shown in Table 8.

The mix of FA50RS25 and FA50RS50 with 50% replacement of FA regardless of W/B showed higher CO₂ reduction rate than OPC100 by 20%, and in terms of compressive strength against CO₂, W/B 0.45 showed better results (Fig. 7). However, the compressive strength of FA50RS25 and FA50RS50 decreased to less than 20% compared to OPC100. CO₂ emissions were slightly higher for FA25RS25 and FA25RS50 with

25% replacement of FA than FA50RS25 and FA50RS50 with 50% replacement of FA. The mix of FA25RS25 and FA25RS50 of W/B 0.45 is satisfactory within the performance maintenance range suggested in this study, and it is considered to be the best mix in terms of compressive strength compared to CO₂ emissions.

The relationship between C_i and normalized flexural strength (Fig. 8). Similar to compressive strength, the combination of FA50RS25 and FA50RS50 showed a high CO₂ reduction rate, but except for the FA50RS25 mix of W/B 0.45, the target performance maintenance range in this study was not met. FA25RS25 and FA25RS50 with 25% replacement of FA were found to





be a better mix to reduce CO₂ emissions and secure flexural strength.

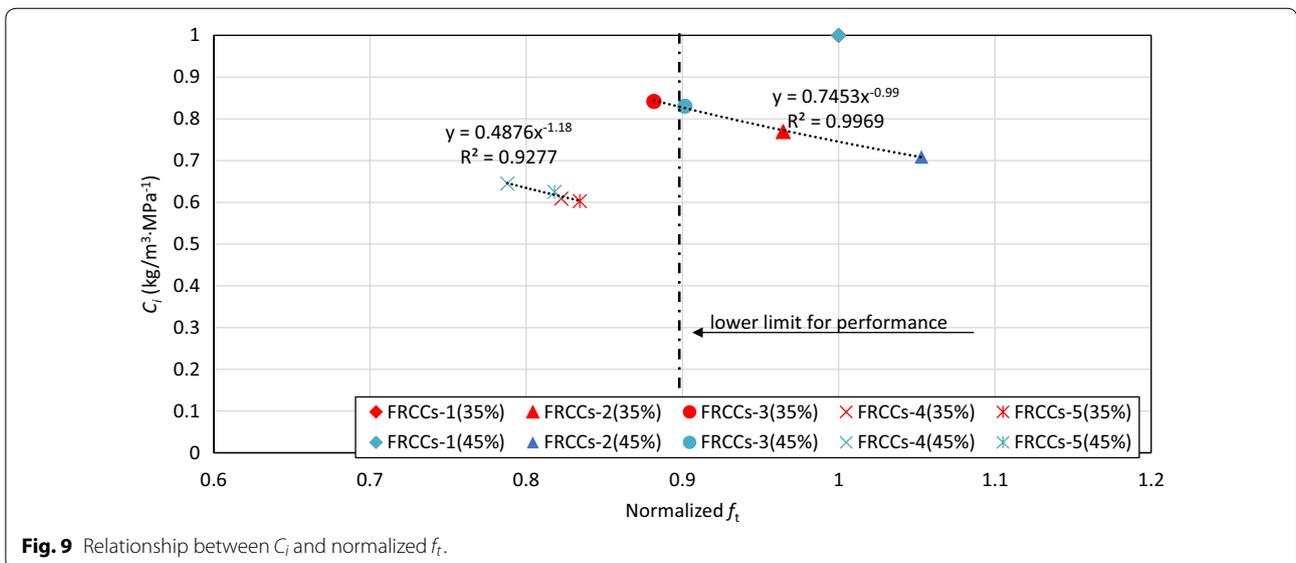
The relationship between C_i and normalized direct tensile strength (Fig. 9). Unlike compression strength and flexural strength, The FA25RS25 and FA25RS50 mixes of W/B 0.45 and the FA25RS25 containing 25% of FA and 25% RSs of W/B 0.35 were satisfactory in the performance maintenance range proposed in this study. In particular, the FA25RS25 mix of W/B 0.45 reduced CO₂ emissions by about 30% compared to OPC100, while the direct tensile strength improved by more than 5%. Therefore, satisfied with the performance maintenance range proposed in this study, and it is considered the best

mix in terms of direct tensile strength compared to CO₂ emission.

As a result, a relatively high correlation coefficient (R^2) between the relationship between the non-dimensional value of the strength and C_i for each experiment is obtained. Hence, the relationship between the CO₂ emission and strengths is helpful in designing a sustainable FRCCs.

5 Conclusions

In this study, FRCCs with recycled materials were fabricated and their mechanical characteristics were evaluated experimentally. In addition, the relationship



between B_i and C_i and mechanical characteristics of FRCCs was compared and analyzed. From the experimental and analytical results, conclusions are summarized as follows.

- (1) As a result of evaluating the mechanical characteristics of MSF FRCCs using recycled materials, comparing to the objective of this study which was OPC 100, the mixtures that resulted more than the 90% of the performance of mechanical characteristics, were FA25RS25 and FA25RS50 of W/B 0.45. Additionally, in comparison with OPC 100, the compressive strength, the flexural strength, and the direct tensile strength of FA25RS25 and FA25RS50 were 95.1% and 94.8%, 105.2% and 110.0%, and 105.3% and 90.2% respectively.
- (2) The lower the W/B, the higher the CO₂ emissions and the difference in CO₂ emissions between W/B 0.35 and W/B 0.45 was 15.3% on average. As the replacement rate of FA increased, the average CO₂ emission decreased by 24.1%, and as the replacement rate of RS increased, the average CO₂ emission increased by 0.7%. Therefore, as a result of the CO₂ emissions at the material stage according to the FRCC mix tested in this study, a greater reduction in CO₂ emission resulted from the replacement rate of FA than W/B, and the CO₂ emission by RS increased, but the difference was not significant.
- (3) B_i was smaller on average as W/B was lower, and the mix of FA replacement was higher than OPC. As the replacement ratio of FA increased, B_i also increased, indicating that the amount of binder to produce unit strength (1 MPa) was higher for FA than that of OPC. As a result of analyzing the relationship between compression, flexural, tensile strength, and C_i , it was found that C_i decreased as the replacement rate of the recycled material increased. The replacement ratio of FA and RS for maintaining the performance of mechanical characteristics of 90% or more compared with the case of no replacement were, the mix of FA 25% and the mix of RS 25%, of W/B 0.45 for compressive strength, the mix of FA 25% and 50% and the mix of RS 25%, of W/B 0.45 for flexural strength. In the case of direct tensile strength, the mix of FA 25% and 50% and the mix of RS 25%, of W/B 0.45 and the mix of FA 25% and the mix of circulating fine aggregate 25%, of W/B 0.35.
- (4) A relatively high correlation coefficient (R^2) between the strengths data and the B_i and C_i is obtained. Hence, the relationship between the binder and CO₂ intensities is helpful in designing a sustainable FRCCs. Furthermore, the CO₂ emission

of a FRCCs can be predicted simply based on information about the type and amount of binder.

- (5) In particular, the mix of FA25RS25 replaced with FA 25% and RS 25% of W/B 0.45, is considered most suitable in terms of performance of FRCCs and reduction of CO₂ emissions.

Acknowledgements

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (NRF-2015R1C1A1A02036481).

Authors' contributions

Y-IJ, W-SP, and H-DY made substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data. J-WL and S-WK analyzed the data and were involved in drafting the manuscript or revising it critically for important intellectual content. All authors read and approved the final manuscript.

Funding

Not applicable.

Availability of data and materials

The authors agree to share their data.

Competing interests

The authors declare that they have no competing interests.

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Received: 22 July 2019 Accepted: 8 January 2020

Published online: 13 April 2020

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