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Effect of Maximum Aggregate Size and Powder Content on the Properties of Self-compacting Recycled Aggregate Concrete

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Abstract

The utilization of recycled aggregates and various industrial by-products is considered a sustainable strategy in the concrete industry. In this study, the effect of the maximum size of recycled coarse aggregate and the cementitious binder content on fresh and hardened properties of self-compacting concrete was investigated. Self-compacting concretes with maximum aggregate sizes of 9.5 mm, 12.5 mm, and 19 mm were prepared at water-to-binder ratios of 0.39, 0.42, and 0.45, respectively. For all mixtures, 100% recycled aggregate was used as coarse aggregate and 60% of cement was replaced by industrial by-products, i.e., fly ash and ground granulated blast furnace slag. The tests included slump flow, air content, hardened density, compressive strength, elastic modulus, and splitting tensile strength. The results showed that the increase in maximum aggregate size and binder content tended to improve both fresh and hardened properties of self-compacting concrete.

Keywords

recycled aggregate, self-compacting concrete, supplementary cementitious materials, cement content, maximum aggregate size

1 Introduction

Self-compacting concrete (SCC), a special type of concrete, is considered one of the most important advances in modern concrete technology. Unlike conventional concrete, SCC has good deformability and cohesion, which enables it to fill molds with its own weight without requiring compaction or vibration. Therefore, SCC has advantages such as reducing labor in concrete pouring work, extending the service life of the formwork, shortening working hours, and improving working conditions by eliminating vibration and noise [1]. SCC requires the following characteristics: (i) filling ability - the ability to flow into the mold and completely fill the space with its own weight; (ii) passing ability - the ability to pass through and flow around a limited space between rebars without separation or blocking; (iii) segregation resistance - the ability to maintain homogeneity and resist segregation of materials during transporting and placing [2]. Due to these requirements, achieving satisfactory workability is generally more difficult than achieving the required strength when designing SCC [3].

From the time SCC was first developed in the 1980s to today, far-ranging research on SCC has been conducted. Several researchers have developed various design methods for SCC mixtures and discussed their rheological and mechanical properties [4–6]. According to a case study investigated by Domone [7], to impart fluidity and viscosity to the SCC mixture, a large amount of cementitious binder of approximately 450–600 kg/m^3 and superplasticizer is required. Since cement is the most expensive component in concrete and has a substantial negative impact on the environment, an economical and eco-friendly mix designs that reduce the cement content in SCC mixture have been proposed [8, 9]. This approach involves the use of industrial by-products such as metakaolin, rice husk, fly ash, slag, and glass powder as supplementary cementitious materials (SCM) in SCC.

The performance of SCC mixtures made from recycled aggregates (RA) has been investigated by several researchers. RA differs from natural aggregates in terms of physical and chemical properties [10], requiring consideration for

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various factors such as properties, size, and particle distribution of RA. In view of the comprehensive reviews on the properties of SCC incorporating RA [11, 12], the parameters considered to be much discussed were the replacement ratio of RA and the addition of industrial by-products and waste in SCC. The increased use of RA reduces the fresh and hardened properties of SCC, while the addition of some industrial by-products can compensate for this adverse effect. However, both RA as concrete material and SCC have been investigated relatively recently, hence, SCC made of RA is not a much-explored area compared to the normally vibrated concrete (NVC) incorporating RA or SCC with natural aggregate. In particular, the effect of maximum aggregate size (MAS) and powder content have been less investigated. Therefore, the aim of this study is to investigate the effect of MAS of RA and cementitious powder content to better understand the fresh rheological and hardened mechanical properties of SCC.

In general, concrete with RA shows inferior mechanical and durability performance than natural aggregate concrete, thus, it is recommended replacing natural aggregate by RA with a limited replacement level. However, the requirements of the physical characteristics of RA for concrete commercially available in Korea are the same as those of natural aggregate, thus, 100% RA was used in all SCC mixtures [13]. In this way, only the effect of the MAS of RA could be investigated. In addition, the effect of the powder content on the properties of SCC was investigated by increasing the powder content while keeping the amount of mixing water constant. 10% and 50% of the total binder content was replaced by fly ash (FA) and ground granulated blast furnace slag (GGBFS), respectively. Consequently, the experimental results were compared with the several prediction models, proving SCC with 100% RA and high volume SCMs can be used in practical engineering.

2 Experimental program

2.1 Materials

Throughout the entire experimental program, commercially produced RA and river sand were used as coarse aggregate and fine aggregate, respectively. The density and water absorption of RA were 2.50 g/cm^3 and 2.87%. The density, water absorption, and fineness modulus of river sand were 2.52 g/cm^3, 1.98%, and 2.68, respectively. In a previous study by the authors [14], adhered mortar content, a characteristic feature of RA, was determined for each size fraction of RA using hydrochloric acid treatment. The adhered mortar contents of 4.75–9.5 mm, 9.5–12.5 mm and 12.5–19 mm RA were 11.5%, 10.5% and 10.0%, respectively.

Ordinary Portland cement (OPC), FA, and GGBFS were used as cementitious binders, and the chemical composition, density, and Blaine fineness of each material are given in Table 1.

In order to ensure the adequate workability of SCC, a polycarboxylate superplasticizer with a specific gravity of 1.04 and a pH of 5 was used.

2.2 Mixture design

To investigate the effect of MAS of RA and powder content on the properties of SCC, 9 series of SCC mixtures were prepared at different MAS (9.5 mm, 12.5 mm and 19 mm) and *w/c* ratios (0.39, 0.42 and 0.45).

The particle size distribution of RA for the mixtures with different MAS was determined according to KS F2527 [13]. SCC with 9.5 mm MAS includes RA in size fractions between 4.75 mm and 9.5 mm. For SCC with MAS of 12.5 mm, the ratios of 4.75–9.5 mm fractions to 9.5–12.5 mm fractions was 4:6 by mass. For a mixture with MAS of 19 mm, the RA proportions of 4.75–9.5 mm, 9.5–12.5 mm, and 12.5–19 mm fractions were 4:5:1 by mass. Partially-saturated RA was used for mixing to compensate for high water absorption of RA. For partial saturation of RA, fully-saturated RA was stored in a laboratory with a controlled temperature and humidity 24 hours prior to mixing. Fine aggregate was used in saturated surface dry condition.

To investigate the effect of powder content, SCC mixtures with increased powder content were prepared by keeping water constant (178 kg/m^3). The powder content ranged from 396 kg/m^3 to 445 kg/m^3. For all SCC mixtures,

Table 1 Chemical and physical characteristics of cementitious binders

Oxide, %	OPC	GGBFS	FA
CaO	59.92	55.74	1.2
SiO_2	20.84	26.56	56.82
Al_2O_3	7.34	10.13	32.1
SO_3	2.1	1.91	1.8
Fe_2O_3	2.80	0.54	3.48
MgO	2.80	3.68	1.61
K_2O	0.91	0.68	0.83
Na_2O	0.14	0.27	0.26
TiO_2	0.62	0.72	0.70
Density, g/cm^3	3.15	2.90	2.20
Blaine fineness, cm^2/g	3380	4360	4610
28-day compressive strength, MPa	53.8	-	-

10% by mass of total binder was FA and 50% was GGBFS. The recommended dosage of superplasticizer provided by its manufacturer was 1% to 3% of the powder content by mass. However, superplasticizer increases the production cost of concrete and has a negative impact on the environment, its dosage was limited to 1% of the powder content for all mixtures.

Detailed mix proportions are presented in Table 2. The codes for SCCs are given as 'SC-water/binder (*w*/*b*) ratio-MAS'. For example, SC-0.45–9.5 stands for SCC with a *w*/*b* ratio of 0.45 and MAS of 9.5 mm.

2.3 Specimen preparation and test methods

A pan mixer with a 60-liter capacity was used for SCC mixing. The mixing procedure was as follows: (i) RA, fine aggregate, and powder (OPC, GGBFS and FA) were added to the mixer and dry-mixed for 2 minutes; (ii) 90% of the mixing water was poured into the mixer and mixed for another 2 minutes; (iii) The superplasticizer was mixed with the remaining 10% of water, put in the mixer, and mixed for 3 minutes. The mixing procedure was kept the same for all mixtures.

After the mixing process, fresh properties were evaluated following the recommendations of Korea Construction Standards [2]. For fresh properties, the slump flow for measuring the workability of SCC and the T_{50} flow time (the time for SCC to reach a diameter of 50 cm, which is measured during slump flow test) for the assessment of segregation resistance were measured according to KS F2594 [15]. Although the standard for air content of SCC mixture is not specified, it was measured according to KS F2421 [16]. The standard [2] requires a slump flow of at least 600 mm, and T_{50} should be in the range of 3 seconds to 20 seconds. Also, after the test, there should be no aggregate pile at the center and no bleeding at the edges.

After fresh property testing, the mechanical properties of the hardened SCC mixtures were determined according to relevant Korean standards [17, 18]. Compressive strength was tested at days 7 and 28, and splitting tensile strength and elastic modulus were measured at 28 days. SCC specimens were cast in 100 × 200 mm cylindrical plastic molds without compaction and vibration, and were cured in water at 23 ± 2 °C until hardened property testing. Three specimens were used for each test.

3 Results and discussion

3.1 Fresh properties

The slump flow and T_{50} values of SCC mixtures are shown in Fig. 1. According to Korea Construction Standards [2], a minimum slump flow of 600 mm is required for SCC, and the slump flows of all SCC mixtures ranged from 610 mm to 700 mm, satisfying the requirements. The test results indicate that mixtures with a larger MAS and higher powder content have an increase in slump flow values compared to mixtures with a smaller MAS and lower powder content. The slump flow of SCC with MAS of 9.5 mm ranged from 610 mm to 630 mm, and that of SCCs with

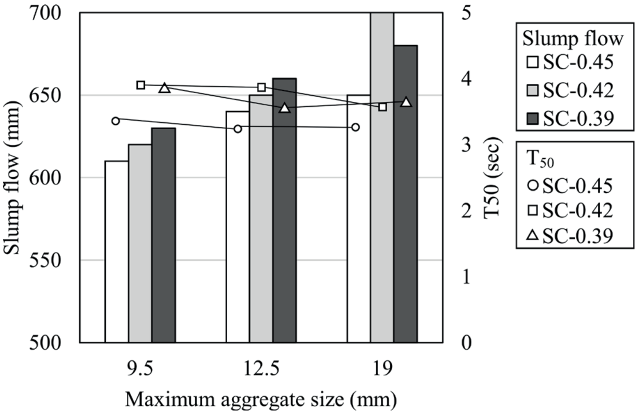


Fig. 1 Slump flow and T_{50} value of self-compacting concrete

Table 2 Mix proportions of self-compacting concrete

ID	*w*/*b*	Water (kg/m^3)	Cement (kg/m^3)	GGBFS (kg/m^3)	FA (kg/m^3)	RA (kg/m^3) 9.5 mm	RA (kg/m^3) 12.5 mm	RA (kg/m^3) 19 mm	Sand (kg/m^3)
SC-0.45-9.5	0.45	178	158	198	40	845	0	0	810
SC-0.45-12.5	0.45	178	158	198	40	338	507	0	810
SC-0.45-19	0.45	178	158	198	40	338	422	85	810
SC-0.42-9.5	0.42	178	170	212	42	832	0	0	799
SC-0.42-12.5	0.42	178	170	212	42	333	499	0	799
SC-0.42-19	0.42	178	170	212	42	333	416	83	799
SC-0.39-9.5	0.39	178	178	222	45	815	0	0	786
SC-0.39-12.5	0.39	178	178	222	45	326	489	0	786
SC-0.39-19	0.39	178	178	222	45	326	407	82	786

MAS of 12.5 mm and 19 mm was 640–660 mm and 650–700 mm, respectively. Small aggregate generally requires more cement paste or mortar to coat the aggregate due to the increased surface area. Therefore, smaller aggregate sizes basically have higher yield stress and viscosity than larger aggregates. Moreover, as shown in Fig. 2, since the air content of SCC made from larger MAS is lower than that of SCC with smaller MAS, less mortar is required to fill the voids between the particles and more mortar can be used to coat the aggregate surface, which reduces yield stress and viscosity, resulting in increased slump flow in SCC [19]. In addition, the adhered mortar in RA can be another parameter affecting the fresh properties of SCC with RA. The adhered mortar absorbs mixing water and deteriorates the workability. In our previous study [14], it was reported that the smaller the aggregate size, the higher the adhered mortar content. Therefore, the workability of the SCC with 9.5 mm MAS is inferior to that of the SCC with 19 mm MAS.

An increase in the powder content is associated with a decrease in aggregate volume in unit concrete. Since the amount of mixing water in all mixtures designed in this study was constant, the decrease in the *w*/*b* ratio was due to the increase in the powder. In Fig. 1, an increased slump flow was clearly observed with the increase of the powder content despite the decrease of the *w*/*b* ratio. Previous study [20] have reported that the increase in the amount of powder better coats the surface of aggregate and reduces the interaction between coarse aggregate particles, thereby lowering the yield stress and increasing shear deformability, contributing to an increase in slump flow.

The value of T_{50} is related to the plastic viscosity of SCC mixture, and the Korea Construction Standards [2] stipulates the requirement in the range of 3 seconds to 20 seconds. The T_{50} values for all mixtures ranged from 3.2 seconds to 3.9 seconds, fulfilling the norm. As shown in Fig. 1, the influence of MAS and powder content on the viscosity of the SCC mixtures appears to be insignificant. SCC mixtures with *w*/*b* ratios of 0.39 and 0.42 showed higher T_{50} values than SCC mixture with *w*/*b* ratios of 0.45, but the difference between maximum T_{50} (SC-0.42-9.5) and minimum T_{50} (SC-0.45-12.5) was only 0.7 seconds.

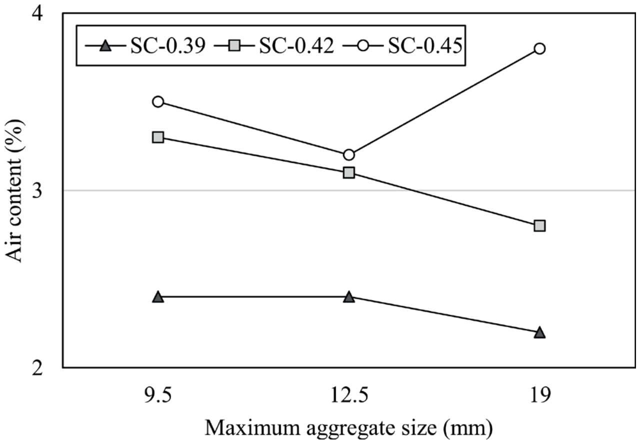


Fig. 2 Air content of self-compacting concrete

The test results for air content are shown in Fig. 2. The air content was inversely proportional to MAS and directly proportional to the *w*/*b* ratio of SCC. Exceptionally, SC-0.45-19 mixture deviated from this trend, which can be attributed to the heterogeneity of the mixture. As shown in Fig. 3 (a) and (b), the segregation of SC-0.45-19 mixture was observed. After slump flow testing, bleeding water was observed at the edges and the aggregates were piled in the center of the mixture. The combination of low powder content, high *w*/*b* ratio, large MAS, and plasticizer dosage may have contributed to the high air content by making the mixture inhomogeneous and segregated [21, 22]. The fresh properties of SCC observed in this study are consistent with a study conducted by Stallings et al. [23]. In the study, it was reported that increasing the amount of powder by 8% and 15% doubled the slump and decreased the air content in concrete.

3.2 Hardened properties

3.2.1 Density

The hardened density was determined by dividing the volume of the SCC specimens by the weight at 28 days. Fig. 4(a) and (b) present the density of SCC by MAS and *w*/*b* ratio, respectively. The hardened density of the SCC mixtures designed in this study ranged from 2275 kg/m^3 to 2340 kg/m^3.

As the MAS of RA and the powder content increases, SCC appeared to become denser. The density of SCC using 19 mm MAS was 0.6% to 2% higher than that of SCC with

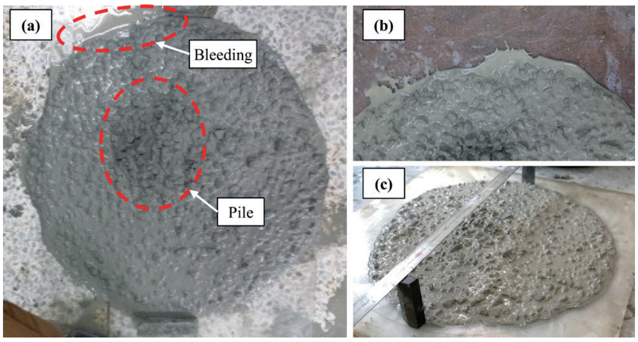
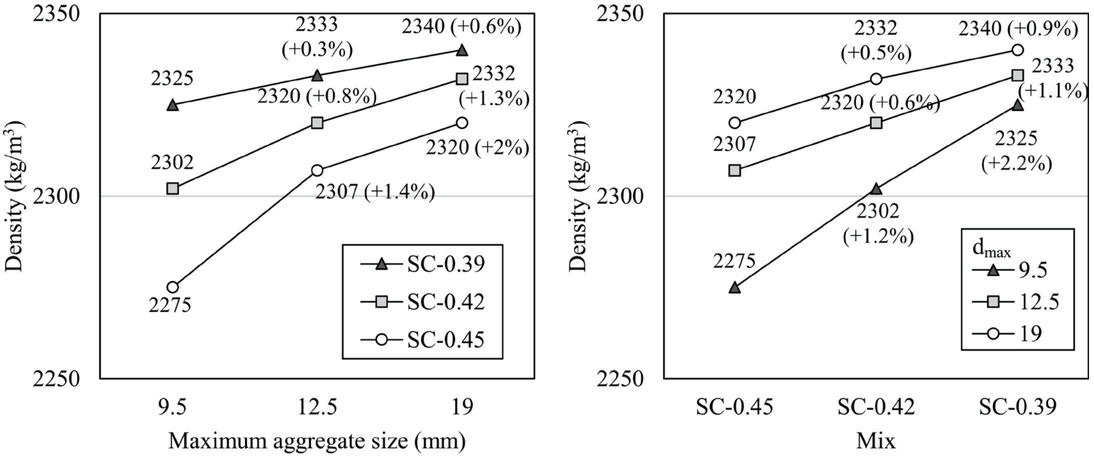


Fig. 3 Slump flow test of self-compacting concrete: (a) and (b) mixtures with segregation; (c) without segregation



(a) (b)

Fig. 4 The 28-day density of self-compacting concrete: (a) by maximum aggregate size; (b) by water-to-binder ratio

9.5 mm MAS. The density increase rate by MAS was particularly greater at high *w*/*b* ratio. The SCC mixture with a *w*/*b* ratio of 0.39 increased the density by 0.6% when the MAS was increased from 9.5 mm to 19 mm, whereas the mixture with a *w*/*b* ratio of 0.45 increased by 2% for a given MAS. Smaller RAs have a higher adhered mortar content than larger RAs, resulting in lower density and higher water absorption [14]. Hence, SCC mixtures made from RA with large MAS exhibit higher density than mixtures with smaller MAS, which is consistent with the results reported in [24].

The variations in the density by *w*/*b* ratio is shown in Fig. 4(b). As observed in the test results for the air content of SCC in the fresh state, a higher *w*/*b* ratio essentially leads to the formation of more pores in the concrete matrix, resulting in a lower density of the mixture. Therefore, at the same MAS, the density of SCC mixtures was higher as the *w*/*b* ratio decreased. Moreover, it has been mentioned above that the decrease in the *w*/*b* ratio in this study was due to the increase in the powder content. OPC and GGBFS, which have higher density compared to RA, contributed to the denser SCC.

3.2.2 Compressive strength

The test results of compressive strength at 7 and 28 days are provided in Fig. 5. Fig. 5(a) and (b) shows the compressive strength at 7 days, and the values ranged from 17.9 MPa to 27.1 MPa. The 28-day compressive strength is plotted in Fig. 5(c) and (d), with values varying from 23.1 MPa to 35.7 MPa.

A clear trend was observed for the compressive strength of SCC to increase with increasing MAS of RA and decreasing *w*/*b* ratio. When the MAS increased from 9.5 mm to 19 mm, the 7-day compressive strength of SCC increased from 5.8% to 13.6%, and the 28-day compressive strength increased from 6.6% to 13.4%. The degree of increase in the compressive strength of SCC by MAS observed in this study is in consistent with the previous studies. In normal-strength concrete, Meddah et al. [25] reported a 12% increase in compressive strength when the MAS increased from 8 mm to 25 mm, and similarly, Xia et al. [26] noted that the compressive strength increased by 23% when the MAS was increased from 9.5 mm to 19 mm. Generically, in normal-strength concrete with RA, the compressive strength is governed by the interfacial transition zone (ITZ) between RA and cement paste, which has the weakest bond [28]. As the MAS increases, the surface area of RA in the concrete matrix decreases, and consequently the perimeter of the ITZ decreases. In other words, concrete with less ITZ develops a distinctly higher strength than concrete with more ITZ. Moreover, the progressive decrease in the adhered mortar content with increasing RA size may have contributed to the further enhancement of compressive strength of SCC with larger MAS.

It is well known that lowering *w*/*b* ratio improves the compressive strength of concrete. When the *w*/*b* ratio decreased from 0.45 to 0.42, the 28-day compressive strength increased by 23.1–29.5%, and when the *w*/*b* ratio was further decreased to 0.39, it increased by 31.9–45.3%. As the *w*/*b* ratio increases, more water exists between the particles and forms more pores in the concrete in the hardened state, which reduce the compressive strength [27].

3.2.3 Splitting tensile strength

The test results for the 28-day splitting tensile strength of the SSC mixtures are shown in Fig. 6. Except for the

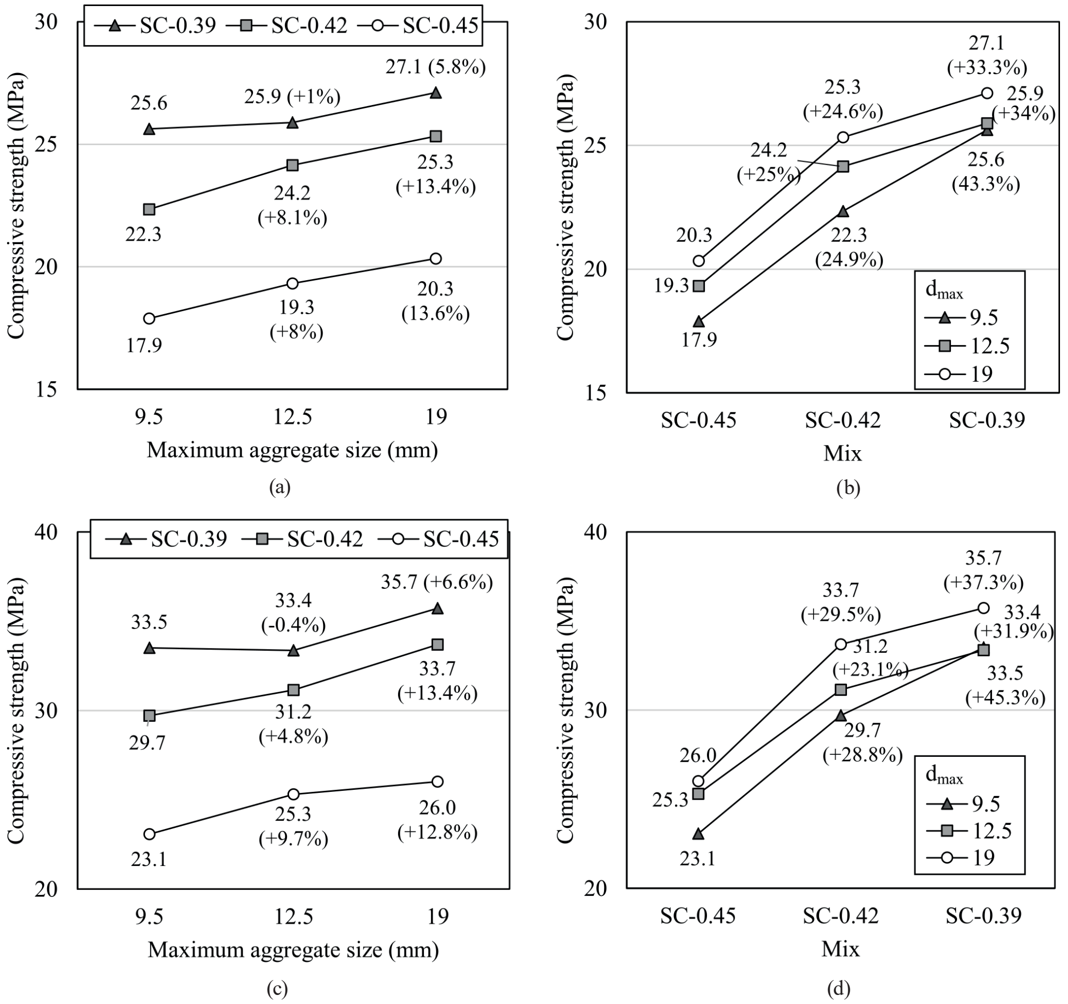


Fig. 5 Compressive strength of self-compacting concrete: (a) by maximum aggregate size at 7 days; (b) by w/b ratio at 7 days; (c) by maximum aggregate size at 28 days; (d) by w/b ratio at 28 days

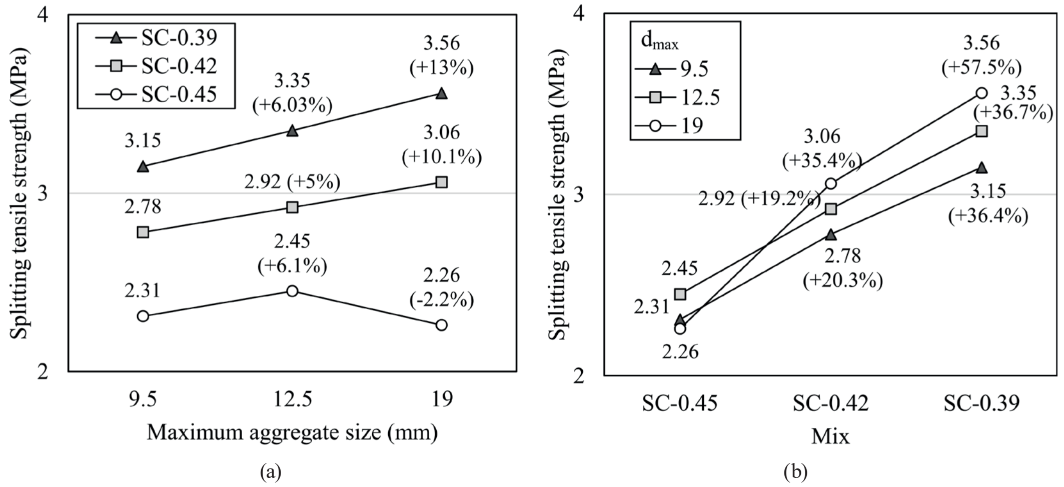


Fig. 6 The 28-day splitting tensile strength of self-compacting concrete: (a) by maximum aggregate size; (b) by w/b ratio

SC-0.45-19 mixture, where inhomogeneity was observed, splitting tensile strength showed a tendency to increase as the MAS and powder content increased. At *w*/*b* ratios ranging from 0.39 to 0.45, the 28-day splitting tensile strength of SCC with the MAS 9.5 mm was 2.31–3.15 MPa, whereas that of concrete with the MAS 12.5 mm increased by 5–6.1% to 2.45–3.35 MPa. The splitting tensile strength of SCC made of RA with a MAS of 19 mm was increased by up to 13%. As the MAS increases, the degree of obstruction of crack propagation in concrete matrix becomes stronger, i.e., crack paths in concrete with larger MAS are more tortuous and longer. On the other hand, concrete with a smaller MAS has a higher amount of aggregate particles and more defects, and shows brittle failure patterns. Therefore, the splitting tensile strength of concrete increases with increasing MAS [30].

Fig. 7 shows the relationship between splitting tensile strength versus compressive strength. In Fig. 7, the prediction models presented by the design code and several researchers are also plotted [31–36]. The coefficient of determination between the compressive strength and splitting tensile strength of the SCC mixtures prepared in this study was 0.916, indicating a strong correlation. The experimental results seem to fit well with the models presented by the ACI committee and Felekoğlu et al. [34]. In particular, the ACI model is based on NVC, but Domone [37] concluded that there was no noticeable difference between NVC and SCC in the relationship between compressive strength and tensile strength.

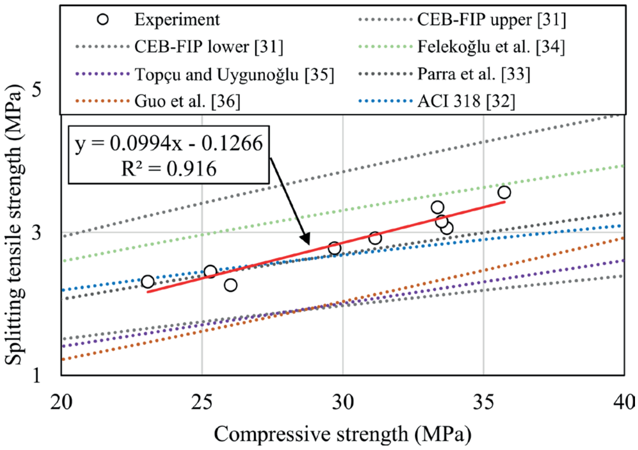
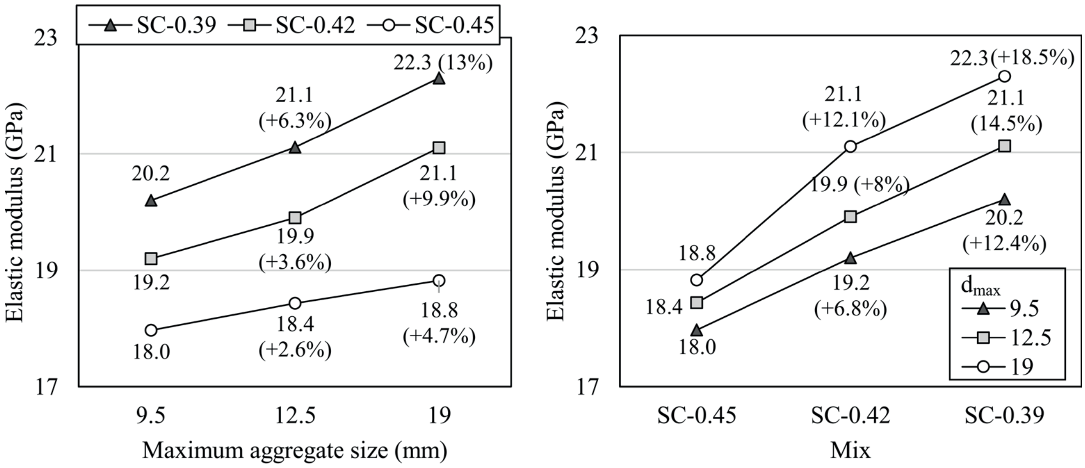


Fig. 7 Relationship between compressive strength and splitting tensile strength

3.2.4 Elastic modulus

Fig. 8 shows the effect of MAS of RA and powder amount on the elastic modulus of SCC, and the increase of these two parameters clearly contributed to the increase of the elastic modulus. The increase in elastic modulus due to larger MAS can be attributed to the characteristics of RA. Because of the adhered mortar, the modulus of RA is lower than that of NA, and in particular, it has been frequently reported that the adhered mortar content is likely to be higher in small sized RA [14]. Thus, RA with a larger particle size has a higher stiffness than RA with a smaller particle size due to a relatively lower adhered mortar content, which also explains the higher elastic modulus in SCC incorporating RA with a large MAS. Moreover, one of the factors that regulates the stiffness of aggregates and pastes is porosity, thus it is natural for concrete containing RA and for concrete with high amount of powder to have a reduced elastic modulus compared to natural aggregate concrete [38].

Prediction models for elastic modulus provided by the design codes [31, 32] and researchers [27, 34, 39, 40] are shown in Fig. 9, and Fig. 9 also presents the experimental results obtained in this study. The increase in the elastic modulus with increasing compressive strength is clearly observed, and the experimental results can provide an acceptable prediction by the model proposed by Persson [40]. However, most of the models presented



(a) (b)

Fig. 8 The 28-day elastic modulus of self-compacting concrete: (a) by maximum aggregate size; (b) by w/b ratio

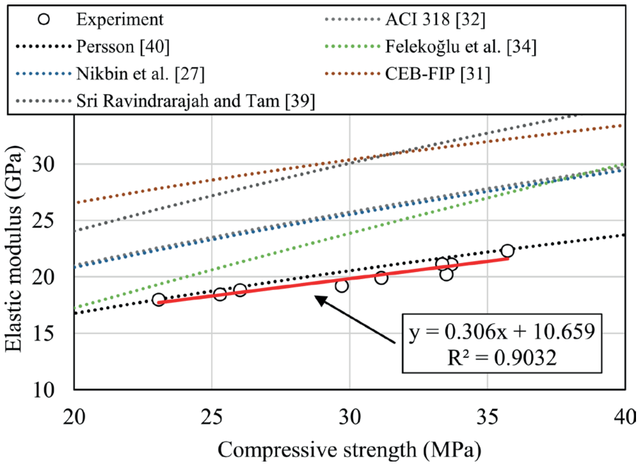


Fig. 9 Relationship between compressive strength and splitting tensile strength

overestimate the elastic modulus in this study. Due to the smaller aggregate particle volume and higher paste content, SCC mixtures generally have a lower elastic modulus compared to NVC. This phenomenon is particularly noticeable in normal-strength concrete. Domone [37] reported that the elastic modulus of SCC was approximately 40% lower than that of NVC for normal-strength concrete, while for high-strength concrete, the difference was less than 5%, which was insignificant.

4 Conclusions

This study investigated the effects of MAS of RA and powder content on fresh and hardened properties of SCC. The following conclusions can be drawn:

- Both the increase in MAS and the amount of powder improved the workability of the SCC mixture. However, the combination of a large MAS and a low powder content lowered the plastic viscosity of the mixture and caused material segregation, which could be compensated by an increase in the powder content.
- The increase in MAS contributed to the increase in workability and mechanical strength by reducing the aggregate surface area, i.e., ITZ, in concrete and improving the aggregate coating. The mechanical strength of SCC with 19 mm MAS was increased by up to 13.6% compared to SCC with 9.5 mm MAS.
- The adhered mortar content of RA was found to decrease with increasing size, which may have contributed to the improvement in the fresh and hardened characteristics of SCC observed in larger MAS.
- The increase in the powder content improved the packing density of the SCC mixture, which contributed to the improvement of mechanical strength. When the powder content was increased from 396 kg/m^3 to 445 kg/m^3, the compressive strength, tensile strength, and elastic modulus of SCC increased by 43.3%, 57.5%, and 18.5%, respectively.
- Compared to traditional compacted concrete, not much research has been done on SCC containing RA. Particularly, the behavior of SCC is expected to be greatly affected by the adhered mortar content of RA. Therefore, in order to build a knowledge system, additional research is recommended with this in mind.

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