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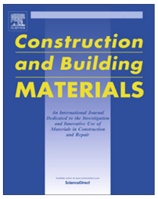

Investigating the effects of steel slag powder on the properties of self-compacting concrete with recycled aggregates

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HIGHLIGHTS

- This study investigated the relationships among multiple mechanical properties of SCRAC.
- Different replacement ratios of SSP had significant impacts on properties of SCRAC.
- SSP improved filling ability and passing ability of SCC, but adversely affected segregation resistance.
- The 10% replacement ratio of SSP was found achieving both superior mechanical properties and better durability.

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ABSTRACT

This study introduced both steel slag and recycled aggregate aiming to improve the sustainability performance of self-compacting concrete (SCC). The study focused on investigating the effects of steel slag powder on the properties of self-compacting concrete with recycled aggregate (SCRAC). Recycled aggregates were used to replace 30% of natural coarse aggregates by volume. The effects of various replacement ratios of steel slag powder (SSP) to Portland cement (i.e., 10%, 20%, 30%, 40%, and 50%) on the workability, mechanical properties, and durability of SCRAC were studied. The results showed that SSP improved filling ability and passing ability of SCC, but adversely affected the segregation resistance. It was found that 10% replacement ratio of SSP to ordinary Portland cement (OPC) in SCRAC showed superior mechanical properties and higher durability performance in resisting chloride penetration and carbonation.

1. Introduction

Self-compacting concrete (SCC) is a high-flow concrete with superior workability which is increasingly used in the construction industry with difficult casting conditions [1–3]. Compared to the conventional concrete, SCC could reduce labor input, decrease construction period, and improve the construction environment [4,5]. However, in comparison with ordinary concrete, the SCC contains a greater amount of cementitious materials, high dosage of admixtures which provides the desired fluidity and viscosity. Considering this fact that production of one tone of Portland cement (PC) releases one tone of carbon dioxide (CO_2) to the atmosphere, the CO_2 emissions could be higher in the manufacturing of SCC if PC is used as the single cementitious material [6,7]. Incorporating industrial wastes such as fly ash, steel slag and recycled aggregates in concrete mix design can improve the sustainability of concrete production by conserving energy and natural resources and reducing costs [8–10]. It has been observed that the SCC mixes containing low and intermediate percentage of recycled aggregates do not report any negative effect on the overall performance of SCC [11,12].

Steel slag, as one type of solid wastes, is a by-product of the steel-making process [13]. It accounts for 10% to 15% of steel products in the manufacturing process by weight [14]. As one of the largest developing economies, China produced about 800 million tons of steel and 100million tons of steel slag in 2016. The production of steel slag is likely to increase due to the increased demand for

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steel. However, the utilization rate of steel slag is currently low in China, and a tremendous amount of steel slag is being dumped into landfills, occupying urban spaces and causing harms to the natural environment [15,16].

Aiming to mitigate the environmental contamination, iron and steel enterprises in China have begun to seek an effective approach to reuse the steel slag. Researchers believe that a promising way to reuse steel slag would be to apply it in concrete mixture. Existing studies showed that steel slag contained somewhat similar chemical composition as cement did, and concrete made from steel slag could fill its internal voids, improve its interfacial bond between particles of binder, and reduce the hydration heat [17–19].

Despite of the ongoing research of applying steel slag in concrete production, its utilization together with recycled aggregates in SCC has not been sufficiently investigated. Due to the high water demand of recycled aggregate, it is expected that incorporation of recycled aggregates in SCC would cause adverse impacts on the fresh properties of SCC [20]. Diao et al. [21] utilized steel slag in SCC with acceptable fresh and mechanical properties to explore the feasibility of incorporating multiple waste streams. So far there are still limited researches in applying recycled aggregates in SCC.

In view of this, the primary goal of this paper is to explore the effects of steel slag powder on the properties of self-compacting concrete containing recycled aggregates. Five different SSP replacement ratios (i.e., 10%, 20%, 30%, 40%, and 50%) were studied. To evaluate the effects of SSP ratios on the workability of SCRAC, the filling ability, passing ability and segregation resistance of different mixture samples were tested. The compressive strength test, splitting tensile strength test and the static modulus of elasticity test were conducted to investigate the effects of replacement ratios of SSP on SCC's mechanical properties. Moreover, the resistance chloride penetration and carbonization test were performed to evaluate the durability properties.

2. Experimental works

2.1. Materials

OPC used in this study was provided by a local cement plant in Zhangjiagang, China. Fly ash (FA) is one of the most important industrial waste products, which due to its chemical composition and hydraulic properties, can be source for new constituent materials in various fields. Fly ash used as a cement replacement in SCC can produce high strength and low shrinkage [22]. So, FA was used in this study as one type of supplementary cementitious material (SCM). FA adopted in this research came from the by-product during the thermal power generation in the local Zhangjiagang power plant in China. SSP was supplied by the Jiangsu Shagang Group, China. After ball-grinding, demagnetizing and screening, the SSP whose fineness was lower than 0.016 mm was selected in this study. The test results complied with GB/T 20491-2006 [23]. The physical properties and chemical compositions of OPC, FA and SSP are presented in Tables 1 and 2.

Medium river sand with well gradation was used as fine aggregate. Crashed stone and recycled aggregate with particle size ranging from 5 to 20 mm were selected as coarse aggregates. Recycled aggregate can be used for coarse aggregate in concrete, which is made of waste concrete crushing, screening and removing impurities [24]. In this study, 30% of natural coarse aggregate (in volume) was replaced by recycled aggregate. The physical properties of fine and coarse aggregates are listed in Table 1.

TOJ800-10 polycarboxylate superplasticizer, supplied by Wuhu Faersheng Technology Co. Ltd, China, was used in SCC to obtain the required fresh properties. This type of superplasticizer had a lower percentage of being attached to the cement surface, and it was manufactured to have superior plasticizing effect with a lower amount added to concrete mixture [25].

2.2. Concrete mix design

A total of mix designs were provided in this study, including a control group, and five other different mixtures with SSP as a partial replacement of OPC at proportions of 10%, 20%, 30%, 40% and 50% respectively by weight. For all AC mixtures, the water-to-binder ratio was designed at 0.33, the binder materials amount (OPC + SSP + FA) was kept at 533 kg/m^3, in which FA was used to replace 20% OPC by weight, recycled coarse aggregate was also used to replace 30% of crashed stone by volume replacement, the additional amount of water is 13.0 kg/m^3 due to the water absorption of recycled aggregates [26–28]. The details of mix proportions of self-compacting concrete are shown in Table 3.

2.3. Material preparation and concrete curing

Before concrete mixing, recycled coarse aggregates were pre-wetted by a part of additional water beforehand. Afterwards, OPC, SSP and FA were mixed with coarse and fine aggregates for 1 min. Then 60% of mixture water was added and mixed for 2 min. Finally, the remaining water was added into the mixture with polycarboxylate superplasticizer and mixed for another 2 min to obtain the homogenous mixture of SCC. Concrete specimens were cast and cured for 24 h at 20 ± 2 °C. After one day, concrete specimens were removed from the mold and cured until the age of testing, at a temperature of 20 ± 2 °C and a humidity of 95% [29].

2.4. Test methods

2.4.1. Fresh properties

Fresh properties of SCRAC with SSP were tested for the filling ability, passing ability and segregation resistance, in accordance with BS EN206-9-2010 [30]. SCC mixtures were tested with slump-flow and slump-flow time (T500). Slump-flow and T500 tests were used to evaluate the filling ability. Passing ability was evaluated by PA value (i.e. the difference between slump-flow and J-Ring flow), and segregation resistance was measured by the segregation percentage.

2.4.2. Mechanical properties

According to GB/T 50081-2002 [29], the compressive strength tests of SCRAC with SSP were based on the 150 mm-sized cubes and 150 mm × 150 mm × 300 mm prisms at curing ages of 3, 7, 28, 90 days. On Day 28, the SCC specimens of 150 mm-sized cubes were prepared for the splitting tensile strength test. Three samples of each group were prepared for the strength test. The arithmetic mean value of the measured values of three samples was taken as the strength result according to GB/T 50081-2002 [29]. If either of difference between the maximum value or the minimum value and the intermediate value exceeds 15%, the intermediate value shall be taken as the strength result. If both

Table 1
Physical properties of materials in self-compacting concrete mixture.

Items	Crashed stone	Recycled aggregate	Natural sand	OPC	FA	SSP
Apparent density (g/cm^3)	2.87	2.60	2.64	3.02	2.42	2.36
Bulk density (g/cm^3)	1.53	1.21	1.54	–	–	–
Water absorption (%)	0.45	4.75	0.4	–	–	–
Void fraction (%)	46.7	53.8	41.7	–	–	–
Crushing index (%)	8.37	14.3	–	–	–	–

Table 2
Chemical compositions of OPC, FA, and SSP.

Items	Component (%)							
	CaO	SiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	SO_3	K_2O
OPC	59.60	20.70	6.20	2.70	0.15	1.30	3.80	0.39
FA	<3	56.79	28.21	5.31	–	5.21	0.68	1.34
SSP	48.00	26.28	11.38	5.24	2.37	4.86	0.98	0.13

Table 3
Mix designs of six SCRAC samples.

Mixes	Weight replacement level (%)	Crashed stone (kg/m^3)	Recycled aggregate (kg/m^3)	Natural sand (kg/m^3)	FA (kg/m^3)	OPC (kg/m^3)	SSP (kg/m^3)	Water (kg/m^3)	Added water (kg/m^3)	Polycarboxylate superplasticizer (kg/m^3)
Control	0	624	267	772	107	426	0	176	13.0	1.16
SSP1	10	624	267	772	107	384	43	176	13.0	1.16
SSP2	20	624	267	772	107	341	85	176	13.0	1.16
SSP3	30	624	267	772	107	298	128	176	13.0	1.16
SSP4	40	624	267	772	107	256	171	176	13.0	1.16
SSP5	50	624	267	772	107	213	213	176	13.0	1.16

the difference between the maximum value or the minimum value and the intermediate value exceeds 15%, the test results of this group were invalid. The static modulus of elasticity of SCC was determined using prism samples.

2.4.3. Durability tests

Two types of durability properties of SCRAC with SSP were tested, including resistance to chloride penetration and carbonation. According to GB/T 50082-2009 [31], three cylinders samples (size of ϕ100mm × 50 mm) were prepared for the coulomb electric flux test. Samples saturated with water in vacuum were then mounted in the test flume. When the electrical power was turned on, the current value through specimens was recorded once every 10 min up to 6 h On Days 28 and 90. Carbonation test was carried out on three specimens of 100 mm-sized cubes at the ages of 28 and 90 days. Upon reaching the curing ages, specimens were transferred from standard curing room to carbonation box with CO_2 concentration at (20 ± 3)% under the room temperature of 20 ± 2 °C and relative humidity at (70 + 5)%. After another 7 days' and 28 days' carbonation, the carbonation depth of samples was measured following ASTM C1202 [32].

3. Results and discussion

3.1. Fresh properties

The test results for fresh properties of SCRAC with SSP were evaluated in terms of filling ability, passing ability and segregation resistance of different mixture samples. The SCC in this study is suitable for ordinary reinforced concrete structure engineering. The targets of SCC mixture is shown Table 4 [33]. The PA is the intermittent passability index of self-compacted concrete which is the difference between slump-flow and J-Ring flow of the concrete. Test results of fresh properties test results are shown in Fig. 1.

Fig. 1 shows that as the replacement ratio of SSP varies, slump-flow of mixtures ranged from 680 mm to 740 mm. It decreased as the SSP replacement ratio increased to 10%, but then increased. That trend was consistent with previous studies of steel slag concrete [34,35]. T500 and PA of SCC samples increased first and then decreased with SSP replacement ratio. The trend of segregation percentage was similar to that of slump-flow. Maximum segregation percentage was 11.78% when the replacement ratio of SSP reached 50%. It was inferred that up to 50% of OPC could be replaced by SSP without adverse effect on fresh properties of SCRAC SSP could improve the workability of SCC, but adversely affected segregation resistance. This could be due to the fact that the stress state between particles and the cohesion among water, aggregate and mortar were changed when SSP was used as SCM in SCC. The initial hydration reaction of cementitious materials containing steel slag was lower due to the low early-age activity of SSP [36]. Therefore, superior workability of SCC containing SSP could be achieved with less water. SCC mixture with SSP decreased the water demand to keep the same workability. The filling, flowing and passing abilities of SCC mixtures were improved as a result, but the segregation resistance was decreased.

3.2. Mechanical properties

3.2.1. Compressive strength

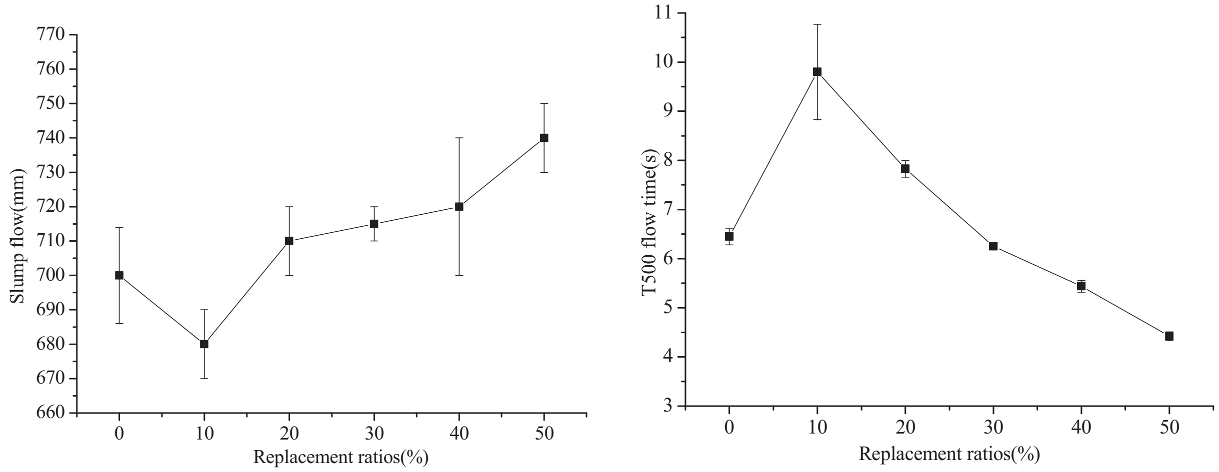
3.2.1.1. Cubic compressive strength. The cubic compressive strength of the six different types of SCC specimens at four different curing ages were obtained as shown in Fig. 2. It can be seen from Fig. 2 that the cubic compressive strength was in the range of 17.3–39.5 MPa, 20.3–42.0 MPa, 28.1–49.0 MPa, 38.3–51.3 MPa at the ages of 3, 7, 28 and 90 days respectively. Samples with different replacement ratios of SSP turned out significant variations of the cubic compressive strength. Fig. 2. is provided to allow the comparison among the six different mixture samples at each curing age.

Fig. 2 shows that during the early curing ages (i.e., before Day 7), replacement ratio of SSP up to 10% did not cause significant change of cubic compressive strength. The growth rates of cubic compressive strength for SCC containing 10%, 20%, 30%, 40%, 50% of SSP were −0.48%, −15.71%, −27.38%, −43.81%, −51.67% respectively on Day 7. As curing age increased, the cubic compressive strength of SCRAC containing 10% of SSP was more significantly higher compared to that of the control group. However, SSP replacement ratios over 20% would cause the reduction of SCC strength. For example, the five different replacement ratios of SSP (i.e., 10%, 20%, 30%, 40%, and 50%) resulted in the strength changes at 6.94%, −6.73%, −18.37%, −29.59%, −42.65% on Day 28 and 8.19%, −7.41%, −16.57%, −20.47%, −25.34% on Day 90 respectively.

The cubic compressive strength at 10% of SSP replacement ratio achieved the highest value on Day 28 and 90. That could be explained by the hydrated products of steel slag—C-S-H gel which improves the density of concrete. However, the cubic compressive strength decreased with the higher percentages (i.e., over 20%) of SSP. According to the composition test results, the active component of steel slag is less than that of cement. So, the concrete strength with steel slag develops slowly. In addition, Wang [37] showed the influence of steel slag on the hydration of cement dur-

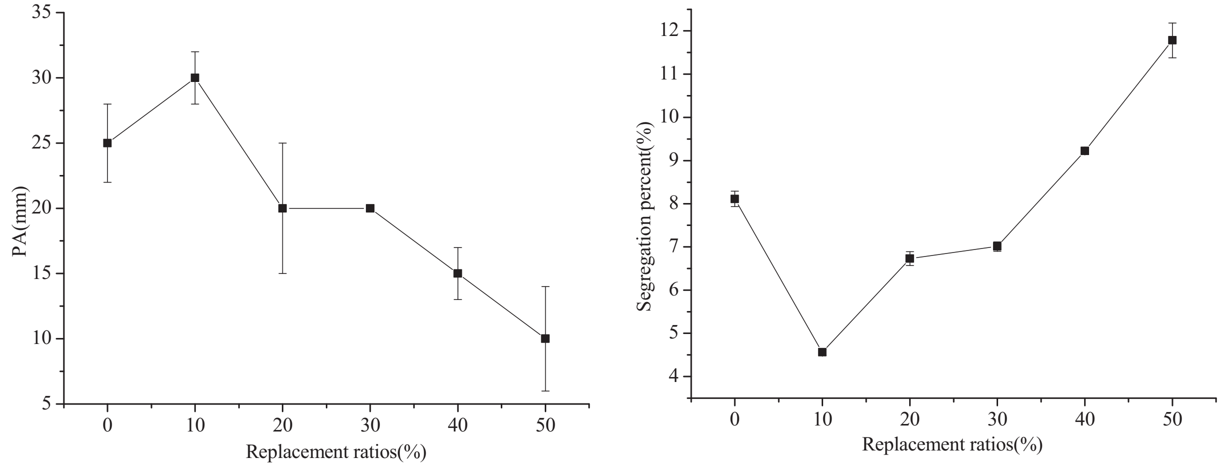
Table 4
Fresh property targets of SCC mixture.

Fresh property	Filling ability		Passing ability	Segregation
	Slump flow (mm)	T500 (s)	PA (mm)	Segregation percentage (%)
Performance Level	SF2	VS1	PA1	SR2
Target	660 ∼ 755	≥ 2	PA1 ≤ 50	≤ 15



(a) Slump flow

(b) T500



(c) PA

(d) Segregation percent

Fig. 1. The fresh properties of SCRAC with SSP at different replacement ratios.

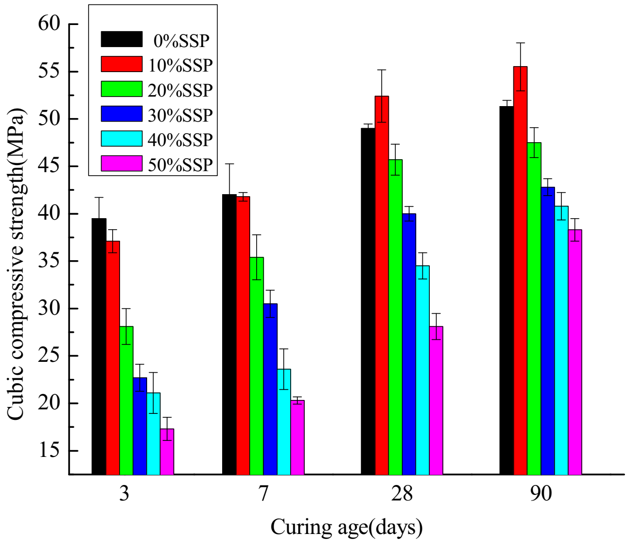


Fig. 2. The cubic compressive strength of SCRAC with SSP at different replacement ratios.

ing the hydration process of complex binder. It was found that steel slag and cement affect each other's hydration by changing the hydration environment. Steel slag does not react with the hydration products of cement. The dormant period of cement-steel slag complex binder during the hydration is longer than that of cement. The larger amount of steel slag would cause a longer dormant period of complex binder.

The longer dormant period of the binary system caused the slower early hydration rate of cementitious materials. As the curing age increase, the inert particles in steel slag are wrapped by the C-S-H gel which is the main cement hydration product. This reduces the cement particle surface C-S-H gel layer thickness indirectly. Moreover, the late hydration environment of cement is improved, promoting the late hydration of cement. Meanwhile, the hydration environment of steel slag is improved. But the bond between inert phase particles and the surrounding C-S-H is weak because of the weak gel of steel slag. Therefore, the SCC strength is reduced. As the amount of steel slag increased, the reduction of strength would be more significant [19,38,39].

3.2.1.2. The effect of SSP replacement ratios on prismatic compressive strength. The prismatic compressive strength test of SCRAC with SSP was performed on Day 28. Test results are demonstrated in Fig. 3. The trend of prismatic compressive strength was consistent with that of cubic compressive strength. A lower replacement ratio (i.e., 10%) of SSP led to increased strength growth, and more than 20% of SSP would cause reductions of prismatic compressive strength. Specifically, the strength change rates were 6.09%, −9.87%, −22.48%, −35.50% and −49.79% respectively compared to that of the control sample, for SSP replacement ratios of 10%, 20%, 30%, 40% and 50%.

3.2.1.3. The relationship between cubic compressive strength and prismatic compressive strength. The relationship between cubic compressive strength and prismatic compressive strength of SCRAC with different replacement ratios SSP is shown in Fig. 4. It is seen from Fig. 4 that the ratio of prismatic compressive strength (f_c) to cubic compressive strength (f_{cu}) ranged from 0.85 to 0.97, with the mean ratio at 0.92, higher than the ratios within ordinary concrete. Fig. 4 displays the linear relationship between f_c and f_{cu} of SCRAC with SSP at the curing age of 28 days which did not match the formula in Chinese code as follows [40]:

$$f_c = \alpha_{c1} f_{cu} \tag{1}$$

where α_{c1} is 0.75 when the concrete strength is less than or equal to C50 concrete; α_{c1} is 0.82 when the concrete is C80 concrete; Linear interpolation method is adopted when the concrete strength is between C50 concrete and C80 concrete.

3.2.2. Splitting tensile strength

3.2.2.1. The effect of the weight replacement level of SSP on splitting tensile strength. Splitting tensile strength test results of all hardened SCC samples are presented in Fig. 5 at the curing age of 28 days. The splitting tensile strength of SCRAC with SSP of 10%, 20%, 30%, 40%, 50% were 3.3 MPa, 2.6 MPa, 2.3 MPa, 2.0 MPa and 1.8 MPa respectively. There is an increase of 6.45%, −16.13%, −25.81%, −35.48%, and −41.94% compared to that of the control SCRAC sample.

3.2.2.2. The analysis of relationships between cubic compressive-splitting tensile strength at the curing period of 28 days. The relationship between cubic compressive strength (f_{cu}) and splitting tensile strength ($f_{t,sp}$) of SCRAC with SSP is illustrated in Fig. 6. Adopting Eq. (2),

$$f_{t,sp} = 0.34 f_{cu}^{0.73} \tag{2}$$

It was found that the formula shown in Eq. (2) was in good agreement describing the relationship between f_{cu} and $f_{t,sp}$ of SCRAC with SSP. A high correlation coefficient with $R^2 = 0.95$ was

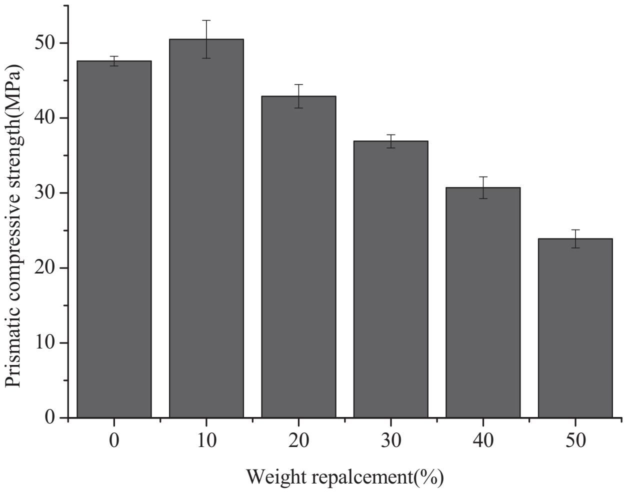


Fig. 3. Influence of SSP replacement ratios on prismatic compressive strength.

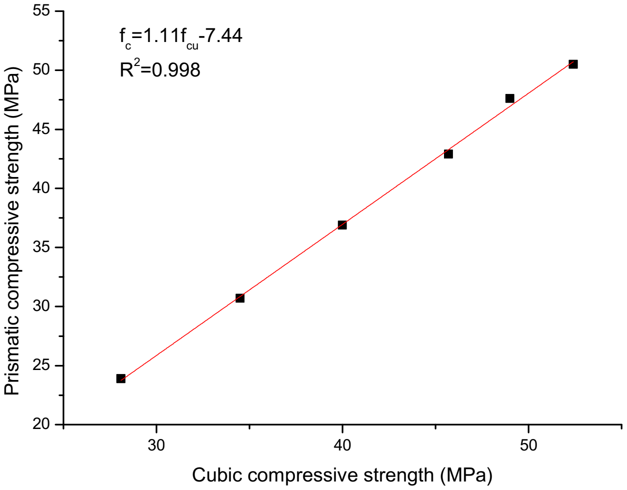


Fig. 4. The relationship between prismatic compressive strength (f_c) and cubic compressive strength (f_{cu}) of SCRAC with SSP on Day 28.

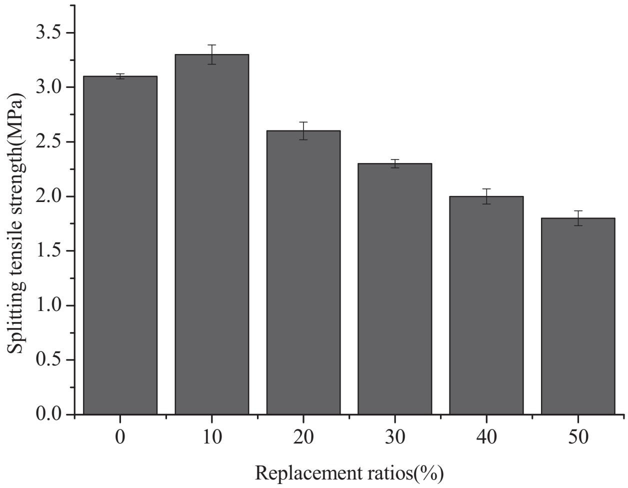


Fig. 5. The splitting tensile strength for various samples.

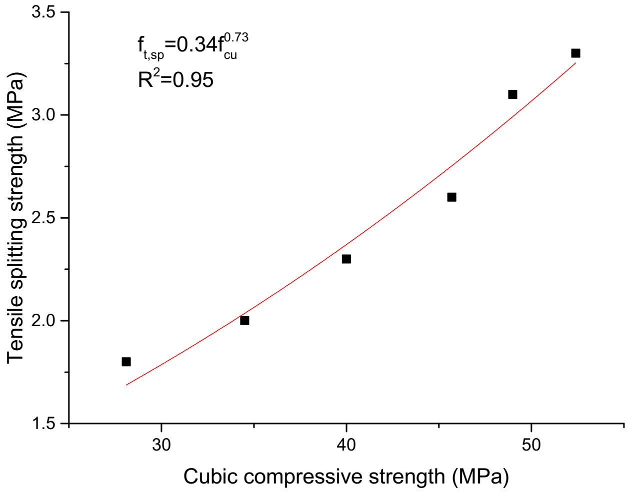


Fig. 6. The relationship between cubic compressive strength (f_{cu}) and splitting tensile strength ($f_{t,sp}$) of SCRAC with SSP on Day 28.

found adopting Eq. (2) in describing the relationship between these two types of strength. The finding was consistent with ACI, CEB and AS in terms of formula capturing the relationship between tension and compressive strength [41–43].

3.2.3. Static modulus of elasticity

3.2.3.1. The effect of replacement ratios of SSP on static modulus of elasticity. Fig. 7 illustrates the change of static modulus of elasticity along with the SSP replacement ratio on Day 28.

The change rates of 5.42%, 1.81%, −3.01%, −4.82%, −9.04% were found in the static modulus of elasticity of SCRAC with different replacement ratios of SSP from 10% to 50%. It was noteworthy that the trend of the change of static modulus of elasticity was generally consistent with that of cubic compressive strength. However, the effect of replacement ratios of SSP on static modulus of elasticity was not as significant as that on compressive strength, according to the percentages of changes.

3.2.3.2. The relationship between cubic compressive strength and static modulus of elasticity. The relationship between cubic compressive strength (f_{cu}) and static modulus of elasticity (E_c) at the age of 28 days is displayed in Fig. 8. It was found that the formula shown in Fig. 8 fitted well with the test results for the high correlation coefficient ($R^2 = 0.935$). However, this was not in agreement with previous results [44–46]. The formula for static modulus of elasticity of ordinary concrete or SCC was not applicable to SCRAC, due to the hydration properties of steel slag and high porosity of recycled coarse aggregates.

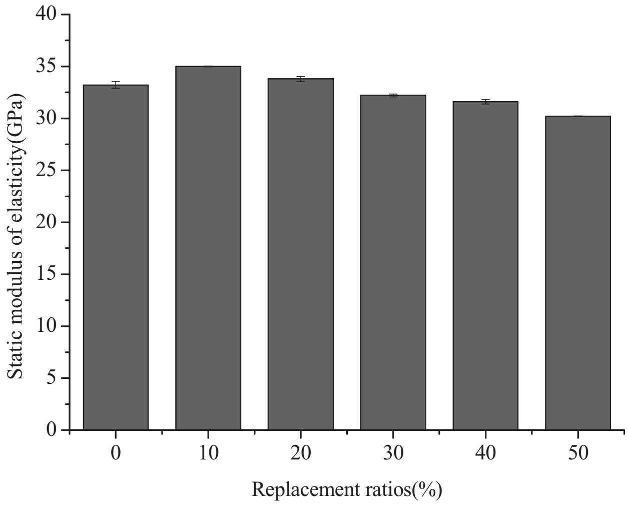


Fig. 7. Influence of SSP replacement ratios on the static modulus of elasticity.

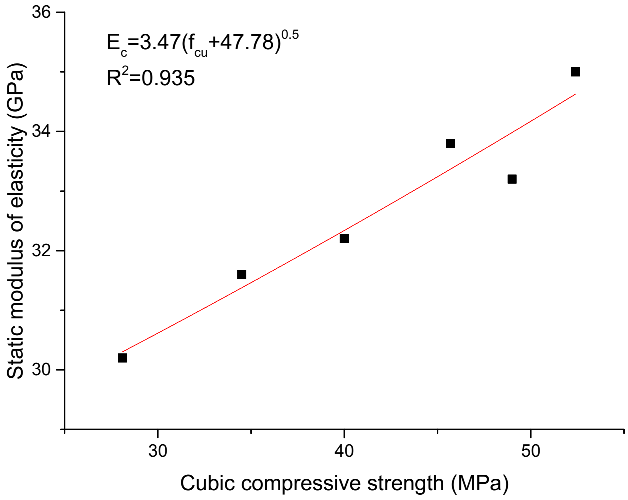


Fig. 8. The relationship between cubic compressive strength (f_{cu}) and static modulus of elasticity (E_c) on Day 28.

3.3. Durability

3.3.1. Resistance to chloride penetration

The resistance of SSP-SCRAC to chloride penetration was based on the coulomb electric flux up to 6 h of samples at curing ages of 28 and 90 days. Test results are presented in Fig. 9. It is seen that the chloride penetration of all specimens was at a low level in Table 5 according to ASTM C1202 [32]. Compared to the control sample, the growth rate of coulomb electric flux in SCRAC containing SSP of 10%, 20%, 30%, 40% and 50% were −17.32%, 29.73%, 75.08%, 77.38%, 130.63% on Day 28 and −5.81%, 10.42%, 78.96%, 81.36% and 163.12% on Day 90. At 10% SSP replacement ratio, the coulomb electric flux through the samples was the lowest. This was because the small amount of steel slag would fill the pores in concrete by hydration reaction, which reduced the porosity of concrete. Therefore, the impermeability of concrete was improved. However, the porosity of concrete would increase with the steel slag content because of more unhydrated particles in steel slag. Therefore, the impermeability of concrete would be reduced. In addition, the weakened chloride resistance of concrete was attributed to Fe element in steel slag [47,48].

In addition, the SCRAC with SSP of 10%, 20%, 30%, 40%, 50% had the growth rates of −50.05%, −43.10%, −57.48%, −48.94%, −48.93%, −43.01% in the coulomb electric flux of SCRAC with SSP on Day 90, in comparison to that of SCRAC with SSP on Day 28. This could be attributed to the complete hydration of cementitious materials as curing period increased, because longer curing time

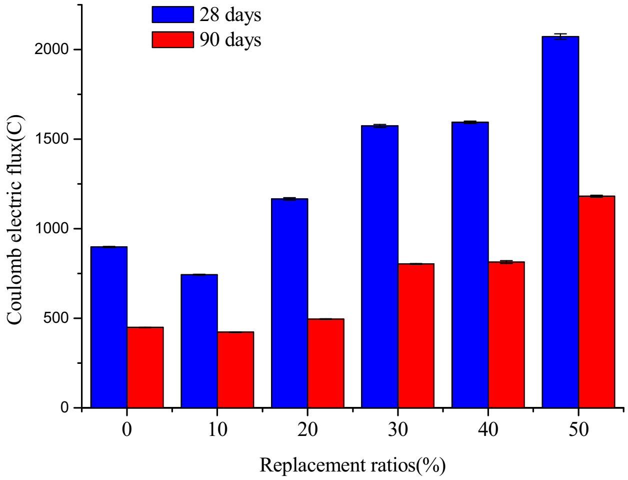


Fig. 9. The coulomb electric flux up to 6 h for samples on Day 28 and Day 90.

Table 5
The relationship between coulomb charge and permeability of concrete.

6 h coulomb electric flux/C	Chloride penetration level
>4000	High
2000–4000	Medium
1000–2000	Low
100–1000	Very low
<100	Negligible

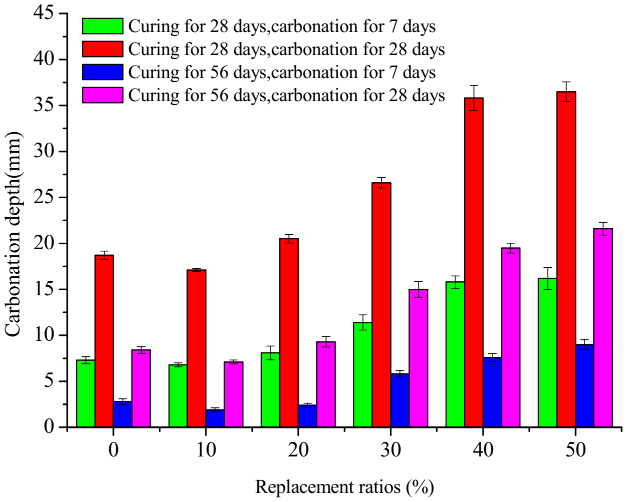


Fig. 10. The carbonation depth of specimens at the ages of 28, 56 days and carbonizing periods of 7, 28 days.

would make concrete denser, and the physical and chemical adsorption of fly ash improved the solidification of Chloride ion in concrete [47,49,50].

3.3.2. Resistance to carbonation

The carbonation depth of all samples at curing ages of 28 and 56 days and carbonation periods of 7 and 28 days is shown in Fig. 10. It was found that under the same condition of curing and carbonation, the carbonation depth of SCRAC with SSP of 10% was the lowest. The growth rates of specimens' carbonation depth were −6.85%, 10.96%, 56.16%, 116.44% and 121.92% for 28 days' curing and 7 days' carbonation. The growth rates of specimens' carbonation depth were −15.14%, 10.71%, 78.57%, 132.14% and 157.14% for 56 days' curing and 28 days' carbonation. It can be seen from the results that specimens under different carbonation and curing periods displayed similar trends of the carbonation depth growth as the replacement ratio of SSP increased.

4. Conclusions

Aiming to achieve environmental friendliness by reusing waste streams, reducing energy consumption in cement manufacturing, and saving natural resources, 30% of virgin aggregates were replaced by recycled aggregate, steel slag power (SSP) was used as SCM (i.e., supplementary cementitious materials) in self-compacting recycled aggregate concrete (SCRAC). The fresh, mechanical, durability properties of SCRAC containing SSP of 10%, 20%, 30%, 40% and 50% were evaluated. The test results revealed that:

- As the replacement ratio of SSP increased, the infilling ability and passing ability of SCC were also enhanced, but the resistance to segregation was decreased.
- The early strength growth of SCRAC with SSP was relatively slow. However, the longer curing period strength of SCRAC with SSP underwent more significant changes. The strength of SCRAC decreased significantly with the increase of SSP replacement ratio over 20%. The maximum compressive strength of SCRAC was found when 10% of SSP was used to replace Portland cement by weight for the considered contents. The ratio at 10% was also identified as the optimal replacement rate to achieve the superior splitting tensile strength and static modulus of elasticity for the considered contents.
- Fitting analyses among different mechanical properties of SCRAC with SSP were performed. Empirical formulas were found with good agreement to describe the relationship between cubic compressive strength and prismatic compressive strength, as well as between compressive strength and splitting tensile strength. Nevertheless, the relationship between compressive strength and static modulus of elasticity could not be best captured using the existing empirical formula, which was only applicable to ordinary concrete or conventional self-compacting concrete.
- The 10% replacement ratio of Portland cement with SSP also resulted in SCRAC with superior durability in terms of resisting chloride penetration and carbonation. But a higher replacement ratio of SSP was found with an adverse effect on the durability of SCRAC. Moreover, the adverse effect on durability performance would be more significant as the curing age increased.

Conflict of interest

None.

Acknowledgments

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