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Research paper

Study on performance of concrete containing different content of steel slag stone in wall brick structure

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Abstract: Steel slag stone can be used as a substitute for coarse aggregate in concrete. In this study, the performance of steel slag concrete (SSC) in the wall brick structure was analyzed. The specimens with a steel slag replacement rate of 0%, 20%, 25%, 30%, 35%, 40%, 45%, and 50% were designed, and the slump, stability, and carbonation resistance were tested. The results showed that the slump decreased with the increase of the replacement rate of steel slag stone. At the 60th min, the slump of SSC50 was 74 mm, which was 25.25% smaller than SSC00. When the replacement rate was more than 30%, cracks or fractures appeared, and the stability was destroyed. Twenty-eight days after the carbonation experiment, with the increase of the replacement rate, the carbonation resistance of the specimen decreased, and the performance was best when the replacement rate was 25%. The experimental results show that the performance of SSC is the best when the replacement rate of steel slag stone is 25%, which can be further promoted and applied in practice.

Keywords: carbonation resistance, concrete, reliability, steel slag stone, wall brick structure

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1. Introduction

In the wall brick structure, in order to ensure the practicability, the concrete used needs to have high performance, not only in mechanical properties such as compressive strength and tensile strength but also in durability, such as carbonation resistance and chloride ion penetration resistance [1]. The durability of concrete refers to the ability of concrete to resist the action of environmental media and maintain a complete appearance and good usability for a long time to maintain the safety and normal use of the structure. The durability of concrete has become one of the important and difficult problems in concrete research [2]. Bravo et al. [3] analyzed the influence of construction waste as recycled aggregate (RA) on concrete durability and collected 33 kinds of concrete containing different construction wastes. The experiment found that the use of RA impacted on the durability, among which the impact on the carbonation resistance was the largest, and the carbonation depth of various RA types increased by 22.2% to 182.4%. Nosouhian et al. [4] used bacteria-producing carbonate to improve concrete performance and compared the durability of bacterial concrete exposed to sulfate. The experiment found that the addition of bacteria reduced the mass, volume change, and water absorption of concrete, enhanced its pressure resistance, and reduced the chloride permeability. Cheng et al. [5] compared the durability of concrete containing 1% nano-SiO_2 and without nano-SiO_2 and found that the addition of nano-SiO_2 could absorb the calcium hydroxide produced by cement hydration and increase the content of calcium carbonate hydrate. Liu et al. [6] treated the surface of the concrete with silane. The experiment found that silane could inhibit the spalling of salt, form a hydrophobic barrier for the entry of external liquid, and restrain ice growth on the surface, thereby improving the anti-freezing performance of concrete. Different amounts and ratios of materials will have an impact on the performance of concrete [7]. Steel slag stone as a high-performance material has been widely used in the construction industry, but its application in concrete is not extensive, and research on the performance of steel slag stone concrete is not yet complete. To understand the performance of steel slag stone concrete better, this study produced and tested specimens with different content of steel slag stone. The author found out the best content that was most suitable for the application in the wall brick structure to provide some theoretical support for its application and promotion in practice.

2. Application of steel slag in the construction industry

Steel slag refers to the solid waste produced in steel-making [8], the amount of which is about 15–20% of the steel output. At present, the utilization rate of steel slag in China is low [9]. A large number of steel slag wastes occupy valuable land [10] and have adverse effects on the environment [11]. Therefore, the efficient utilization of steel slag is a very important issue. At present, steel slag has been widely used in fields such as agriculture and industry [12, 13].

1. Recycle of steel scrap [14]: many steel plants treat steel slag by the wet water cooling method. Through steps such as crushing and magnetic separation, small and medium pieces of steel scrap and iron powder are separated and returned to smelting. About 15% of steel and 85% of slag can be separated by magnetic separation. With the development of technology, the tank-type hot disintegrating method has also been applied in steel plants, and the quality of iron separated by magnetic separation is also higher.
2. Steel slag cement [15]: when steel slag is used in the production of cement, the strength of cement can be improved when the dosage was between 20% and 25%; however, this method is rarely used in practice because of the large fluctuation of the composition of steel slag.
3. Building backfill [16]: the hardness and shape of steel slag are very suitable to be used as backfill materials, and it has been successfully applied in projects such as road embankment, land reclamation, and engineering backfill.
4. Road engineering [17]: steel slag can be used in the base, cushion, and surface of the road after it is combined with fly ash and cement. The application of steel slag in the pavement can enhance the wear resistance and skid resistance of the pavement. It is also suitable for repairing the pavement in winter.
5. Concrete [18]: steel slag is used as the substitute for aggregate to produce steel slag concrete (SSC), which plays a good role in improving the basic mechanical properties of concrete. It has been applied in practice.

3. Research methods

3.1. Raw materials

Cement: Shanshui brand P.O42.5 cement (Shanshui group). Its performance and chemical composition is shown in Table 1.

Fine aggregate: natural river sand (Beijing Jingyulu Construction Engineering Co., Ltd.). Its performance is shown in Table 2.

Coarse aggregate: steel slag stone (Shandong Jinan Iron and Steel Group) and natural gravel (Beijing Jingyulu Construction Engineering Co., Ltd.). Their performance is shown in Table 3. The sieving curve of steel slag stone is shown in Fig. 1, and its chemical composition is shown in Table 4.

Fly ash: first-class fly ash (Hebei Baoting Engineering Construction Co., Ltd.). The performance is shown in Table 5.

Water: ordinary tap water.

Water reducing agent: naphthalene water reducer (Jinan Qianqi Chemical Co. Ltd.) with a water-reducing rate of 20%.

Table 1. Basic properties of cement

		P.O42.5
Density/(g/cm^3)		3.15
Specific surface area/(m^2/kg)		331
Initial setting time/min		98
Final setting time/min		205
28 d flexural strength/MPa		8.1
28 d compressive strength/MPa		44.2
Chemical composition/%	SiO_2	21.85
	Al_2O_3	5.02
	Fe_2O_3	3.98
	CaO	62.60
	MgO	2.41
	MnO	0.07
	SO_3	2.03

Table 2. basic properties of coarse aggregate

	Natural river sand
Mud content/%	2.2
Fineness modulus	2.8
Apparent density/(g/cm^3)	2.5
Bulk density/(g/cm^3)	1.6

Table 3. Basic properties of coarse aggregate

	Steel slag stone	Natural gravel
Apparent density (kg/m^3)	3720	2664
Bulk density (kg/m^3)	1920	1400
Compact density (kg/m^3)	2100	1500
Needle flake content (%)	1.8	6.3
Water absorption (%)	1.2	1.0
Crushing index (%)	6.9	6.6
Gradation range	5–20	5–25

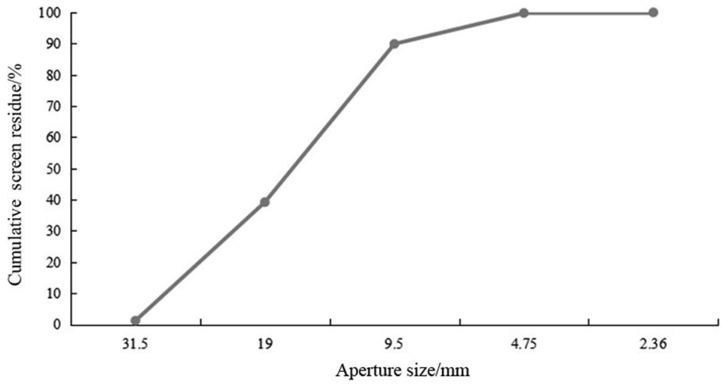

Fig. 1. The sieving curve of steel slag stone

Table 4. The chemical composition of steel slag stone

Components	Content (%)
CaO	50.52
Fe_2O_3	23.46
SiO_2	12.62
MgO	3.74
Al_2O_3	2.88
P_2O_5	2.52
MnO	2.41
TiO_2	1.24
Cr_2O_3	0.58
Na_2O	0.02
S	0.01

Table 5. Basic properties of fly ash

	First-class fly ash
Density (g/cm^3)	2.2
Fineness (%)	4.2
Water demand (%)	94
Loss on ignition (%)	1.95
Water content (%)	0.2

3.2. Specimen preparation

Taking C30 concrete as the design standard and referring to *Specification for Mix Proportion Design of Ordinary Concrete (JGJ55-2011)*, the proportion of steel slag stone replacing natural gravel was 0%, 20%, 25%, 30%, 35%, 40%, 45%, and 50%, respectively, under the condition of constant water-glue ratio. The mix proportion of SSC is shown in Table 6.

Table 6. Mix proportion design of specimens

Number	Cement (%)	Fly ash (%)	Natural gravel (%)	Natural river sand (%)	Steel slag stone (%)	Water (%)	Water reducing agent (%)
SSC00	70	25	51.57	100	0	6.43	0.15
SSC20	70	25	41.26	100	20	6.43	0.15
SSC25	70	25	38.68	100	25	6.43	0.15
SSC30	70	25	36.10	100	30	6.43	0.15
SSC35	70	25	33.52	100	35	6.43	0.15
SSC40	70	25	30.94	100	40	6.43	0.15
SSC45	70	25	28.36	100	45	6.43	0.15
SSC50	70	25	25.79	100	50	6.43	0.15

The concrete was mixed using a single horizontal-shaft forced mixer. The coarse aggregate, fine aggregate, cement, fly ash, and water were added in turn and mixed evenly. Then they were placed in the mold and vibrated. The mold was removed after 24 hours of standard curing, and the curing continued for 28 d.

3.3. Performance test

1. Slump test: the mixture was put into a slump test cylinder and evenly mixed by a steel rod. After the third time of mixing, the mixture overflowing from the edge was removed, and the cylinder was quickly lifted to measure the slump. The test was conducted again 30 min and 60 min after the first measurement.
2. Autoclave test: according to the method described in GB/T750-1992, an autoclave test was carried out to determine the stability of the test specimen. The size of the test specimen was $40 \times 40 \times 160$ mm, and three test specimens were used. After curing for 24 h, the test specimen was put into a boiling box for three-hour boiling and then placed in an autoclave with a pressure of 1 MPa. After curing for eight hours, the state of the test specimen was observed.
3. Carbonization test: a carbonization test was carried out according to the method described in GB/T50080-2009 to determine the carbonization resistance performance of the test specimen. The size of the test specimen was $100 \times 100 \times 100$ mm. The

number of specimens was three for every age. After 28 days of standard curing, the test specimen was put into a 60° drying oven for 48-hour drying and put into a carbonization test chamber (Fig. 2). Carbonization was performed under a temperature of 20°, a humidity of 70%, and a CO_2 concentration of 20%. After curing for three days, seven days, 14 days, and 28 days, the specimen was taken out and split to remove the floating ash. 1% phenolphthalein alcohol solution was sprayed on the fracture surface, and the carbonation depth was measured after drying.

Fig. 2. A carbonization test chamber

4. Results

The slump change of different mixtures is shown in Fig. 3.

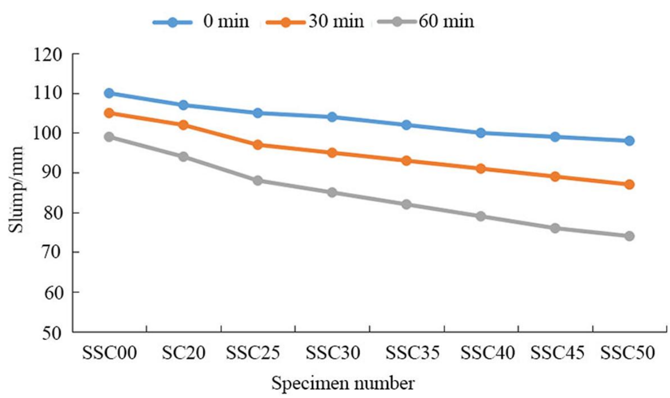

Fig. 3. Slump test results

It was seen from Fig. 3 that the slump of SSC00 was the largest, followed by SSC20, SSC25, SSC30, SSC35, SSC40, SSC45, and SSC50; the slump of SSC decreased with the increase of the steel slag replacement rate; with the passage of time, the slump of the specimen became smaller and smaller; at 0 min, the slump of SSC00 was 110 mm, and the slump of SSC50 was 98 mm, which was 10.91% lower than SSC00; at 60 min, the slump of SSC00 was 99 mm, and the slump of SSC50 was 74 mm, which was 25.25% lower than SSC00. In terms of slump,the replacement rate of steel slag stone cannot be too high in order to ensure the working performance of concrete, otherwise it will lead to a decrease in the fluidity of concrete, which is not conducive to the production of specimens.

The bulk density of the concrete is shown in Table 7.

Table 7. The bulk density of the concrete

Number	Bulk density (kg/m^3)
SSC00	2308.67
SSC20	2311.42
SSC25	2315.56
SSC30	2316.77
SSC35	2318.89
SSC40	2321.12
SSC45	2323.54
SSC50	2325.67

It was seen from Table 7 that the density of the concrete gradually improved with the increase of the replacement rate of steel slag stone. When the replacement of steel slag stone was 0%, the density of the concrete was 2308.67 kg/m^3; when the replacement of steel slag stone was 50%, the density of the concrete was 2325.67 kg/m^3, indicating that the higher the replacement rate of steel slag stone was, the higher the density of the concrete was.

After the autoclave test, the stability results of different specimens are shown in Table 8.

Table 8. Stability test results

Number	Stability results
SSC00	Qualified
SSC20	Qualified
SSC25	Qualified
SSC30	Qualified
SSC35	Crack
SSC40	Crack
SSC45	Fracture
SSC50	Fracture

It was seen from Table 8 that when the replacement rate of steel slag stone was lower than 30%, SSC had good stability. With the increase of the replacement rate, the specimens began to be damaged. A large number of cracks appeared in SSC35 and SSC40 after autoclave, and fracture occurs in SSC45 and SSC50 after autoclave, showing that the stability of specimens decreased with the increase of steel slag stone content. When the replacement rate of steel slag stone exceeded 30%, cracks and fractures appeared in the specimen. The reason for the above result might be because a large amount of dead-burned f-CaO in steel slag stone reacted with water under the condition of autoclave to form $Ca(OH)_2$, and the volume expanded violently, which led to the destruction of the specimen. Therefore, the replacement rate should not be more than 30% in order to ensure its autoclave stability, otherwise it will lead to poor stability, which is not conductive to practical application.

The carbonation depth of different specimens is shown in Fig. 4.

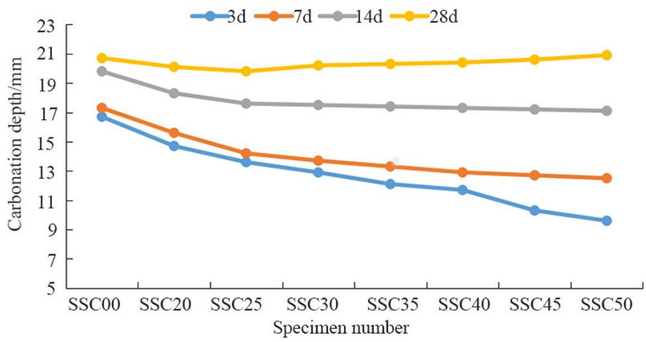

Fig. 4. Variation of carbonation depth of specimens

It was seen from Fig. 4 that with the increase of the carbonization time, the carbonization depth of SSC was deepened, and the carbonization depth at the 28th day was significantly larger than that at the 3rd day. Specifically, on the 3rd day, i.e., in the early stage of the carbonization experiment, the higher the replacement rate of steel slag stone was, the smaller the carbonization depth of the specimen was, i.e., the better the carbonization resistance was. The carbonization depth of SSC00 was 16.7 mm, while that of SSC50 was 9.6 mm, 42.51% smaller than SSC00. With the extension of the experimental time, the improvement of the carbonization resistance performance of steel slag stone began to change. When the carbonization time was 28 days, with the increase of the replacement rate of steel slag stone, the carbonization depth decreased first and then increased, i.e., the carbonization resistance performance of SSC increased first and then decreased. Taking SSC25 as the boundary, when the replacement rate was lower than 25%, the carbonization resistance performance was better; when the replacement rate was larger than 25%, the carbonization resistance performance of SSC decreased. The carbonation depth of SSC00 was 20.7 mm. The carbonation depth of SSC25 was 19.8 mm, which was 4.35% smaller than SSC00. The carbonation depth of SSC30 was 20.2 mm, which was only 2.42% smaller than SSC00. The carbonation depth of SSC50 was 20.9 mm, which was 0.97% larger than

SSC00. In general, the suitable replacement rate of steel slag stone was 25%, otherwise the addition of steel slag stone cannot improve the performance of concrete but will cause a decrease in the resistance to carbonation. In order to improve the availability of steel slag stone concrete in wall block structures, the replacement rate of steel slag stone should be controlled within a reasonable range according to the experimental results.

5. Discussion

With the rapid development of the economy, the pressure on the environment is also increasing day by day. The problems of environmental pollution and resource shortage caused by traditional concrete production are also becoming more and more serious [19]; therefore, people put forward new requirements for the treatment of industrial solid waste, including improving industrial solid waste recycling to realize zero-emission. The use of waste materials in concrete mixtures can help people to protect the environment and achieve environmentally friendly concrete design [20]. Steel slag is an industrial solid waste with the highest output [21], whose treatment method has been widely concerned. In the field of concrete, with the reduction of natural aggregate [22], people began to look for feasible alternatives [23], such as waste glass [24], waste porcelain [25], copper tailings [26], recycled aggregates [27], etc. In the wall brick structure, the walls made of bricks are connected together by concrete. Therefore, the performance of concrete has a great influence on the overall performance of the building. The higher the performance of concrete is, the better the performance of a wall block structure is, the better the performance and durability of a building is. Therefore, studying the performance of concrete is quite necessary.

This study mainly analyzed the concrete containing steel slag stone and its performance and compared the specimens with different steel slag stone replacement rates. In the perspective of working performance, the addition of steel slag stone had an impact on the flow performance of the specimen; the higher the replacement rate was, the smaller the slump of the specimen was, which showed that the replacement rate of steel slag stone could not be too large in order to ensure the working performance of the specimen. In the perspective of stability, when the replacement rate of steel slag stone was greater than 30%, the stability of the specimen was damaged; as the replacement rate continued to increase, the specimen cracked or damaged, which could not meet the needs of the application in the wall brick structure. Therefore, in practical application, the replacement rate of steel slag stone should not be greater than 25%. Finally, from the perspective of the carbonization resistance performance, with the progress of the carbonization experiment, the carbonization degree of different specimens gradually deepened. In the early stage of the experiment, the higher the replacement rate of steel slag stone was, the better the carbonation resistance of the specimen was. But in the later stage of the experiment, with the increase of the replacement rate of steel slag stone, the carbonation depth of the specimen increased, i.e., the carbonation resistance decreased. In conclusion, the suitable replacement rate of steel slag stone was 25%.

In this study, although the research on the performance of SSC in wall brick structure has obtained some results, there are still some shortcomings. In future work, we will:

1) study more performances of SSC;
2) compare the performance of steel slag extracted by different methods in concrete;
3) study the application performance of SSC in the specific wall brick structure.

6. Conclusions

This study analyzed the performance of concrete containing steel slag stone in the wall brick structure. Coarse aggregate was replaced by steel slag stone, and the performance of SSC with different replacement rates was compared. It was found that the increase of steel slag stone could reduce the slump of concrete. When the replacement rate exceeded 30%, the stability of the specimen was damaged. In the later stage of the experiment, with the increase of the replacement rate of steel slag stone, the carbonization resistance decreased. In conclusion, when the replacement rate of steel slag stone was 25%, SSC presented the best performance. The experimental results show that the steel slag stone effectively improves the performance of concrete, which provides some reliable support for its further application in the wall brick structure.

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