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Fatigue characteristics of steel-making slag concrete under compression in submerged condition

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HIGHLIGHTS

- Formulae for predicting the fatigue life of SSC under compression are proposed.
- Fracture morphology of SSC depends on the types of steel-making slag aggregates.
- Applying polished slag aggregates is found to improve the fatigue strength of SSC.
- Non-easiness of micro-crack nucleation is attributed to the improvement.

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ABSTRACT

Steel-making slag concrete (SSC) is an environmental friendly material made mainly of by-products of steel industry without using Portland cement. The fatigue characteristics of SSC under compression in submerged condition are experimentally investigated, for applications to marine and harbor structures. Based on the fatigue tests, calculation formulae are proposed on the averaged fatigue life. The fatigue strength of SSC with hot metal pretreatment slag or converter slag as fine and coarse aggregates is slightly smaller than that of ordinary cement concrete, while using polished hot metal pretreatment slag (PHPS) as aggregates is found to improve the fatigue strength of SSC. The superior characteristics of SSC with PHPS against fatigue failure are studied through the measurements of strain, AE, and hardness of the materials.

1. Introduction

Steel industry is one of the key industries worldwide. In the steel-making process, huge amount of steel slag is generated as by-product. Steel slag is classified into "blast-furnace slag" and "steel-making slag". These slags are widely used in the field of construction in Japan. Most part of the blast-furnace slag is consumed as material of cement, and remaining is used for road constructions, ground improvements, aggregates, and so on. The recycle rate of blast-furnace slag is almost 100%. Although steel-making slag is also utilized in the field of construction, the recycle rate is about 98%, during 3 years from 2010 to 2012 [1]. About 0.28 million ton per year of steel-making slag was landfilled during these periods. Steel-making slag is by produced in the steel-making process in which such impure substances as C, S, Si, P, and so on, are removed from hot metal and scrap [2]. Among steel-making slags, hot metal pretreatment slag is by produced after the removal of S, Si, and P before the decarburizing process, while converter slag is by produced after the decarburizing process in a converter furnace. Since residual capacity of landfill sites is surely decreasing and construction projects tend to decline due to the recent

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recession, it becomes further difficult to consume steel-making slag. Developing technologies utilizing steel-making slag is an urgent issue.

Steel-making slag concrete [3], hereafter it is referred as SSC, is made of ground granulated blast-furnace slag, steel-making slag, pozzolan (e.g. coal fly ash), and alkaline activator (e.g. lime hydrate). SSC can be made with the same facilities and processes as ordinary cement concrete (OCC), and becomes solidified by the latent hydraulicity of ground granulated blast-furnace slag, to the same strength level as OCC. SSC is recognized as one of the eco-friendly concretes [4], which contributes to resource circulation and low-CO_2 emission. Although the available references on such concretes are limited at the present, major features of SSC are summarized as follows: (1) most of raw materials are industrial by-products, (2) Portland cement is not necessarily required, (3) constituents of iron, silica and so on are good for growth of creatures.

SSC is suitable to be applied to marine and harbor structures, from the following reasons: (1) steel-making slag and ground granulated blast-furnace slag are mainly made at oceanfront steel plants, (2) SSC has a high resistibility against abrasion [5], (3) SSC has a lower alkaline-elution property and a higher marine biofouling than OCC [2]. SSC can be also used as wave-dissipating blocks, seaweed bed blocks, fish reef blocks, and so on. When SSC is applied to these structures, it is subjected to repeated stresses mainly from tidal wave. Therefore, considering the safety of SSC against fatigue failure is indispensable in the design stage. The fatigue strength of SSC under repeated bending stress is reported to be about the same as that of OCC [5], while have been few researches reported on the fatigue strength of SSC under repeated compressive stress. Thus, the fatigue characteristics of SSC under compression in submerged condition are studied.

The first and second authors [6] have reported on the fatigue strength of SSC with hot metal pretreatment slag and polished hot metal pretreatment slag as fine and coarse aggregates under compression in submerged condition. The fatigue strength of SSC with converter slag as fine and coarse aggregates under compression in submerged condition is also studied in this paper, considering the converter slag has a higher density, lower water-absorption rate, and higher crushing load than hot metal pretreatment slag. The influence of the type of steel-making slag aggregates on the fatigue characteristics of SSC under compression in submerged condition and the mechanisms are also discussed.

2. Experiments

2.1. Materials and mixture proportion

Table 1 summarizes the physical properties of materials used. Here, HPS means "hot metal pretreatment slag", PHPS means "polished hot metal pretreatment slag", and CS means "converter slag". Ground granulated blast-furnace slag was used as main binder of SSC. Coal fly ash was the second grade specified in JIS A 6201 [7], and was used for a long-term strength and low-alkaline elution due to pozzolanic reactivity. Lime hydrate was used as alkaline activator of GGBFS. No chemical admixture was used. The steel-making slags were aged before being used, to avoid the expansion of specimen from the hydration of free-CaO and free-MgO. Major chemical compositions of the steel-making slags used are listed in Table 2.

Table 2
Major chemical compositions of the steel-making slags used.

	T. Fe	CaO	SiO_2	MgO	Al_2O_3
HPS	14.3	34.9	28.5	3.6	9.4
CS	19.7	43.3	12.7	5.9	2.9
					(mass%)

The mixture proportions of SSC are presented in Table 3. In the table, "strength indicator" expresses the degree of strength development of SSC. Based on the experiments, the following equation has been proposed [2].

$$\text{Strength indicator (S.I.)} = (GGBFS + LH + 2OPC + 0.35CFA)/W \quad (1)$$

where *GGBFS* is the unit content of ground granulated blast-furnace slag (kg/m^3), *LH* is the unit content of lime hydrate (kg/m^3), *OPC* is the unit content of ordinary Portland cement (kg/m^3), *CFA* is the unit content of coal fly ash (kg/m^3), and *W* is the unit content of water (kg/m^3). The strength indicator is comparable to the cement-to-water ratio in OCC. In general, the compressive strength of SSC becomes larger with increase in the strength indicator. A pair of strength indicators was adopted in this study: 2.17 as normal strength level and 3.50 as middle strength level.

2.2. Preparation of steel-making slag aggregates

Fig. 1 shows the preparing methods of the steel-making slag aggregates. In the process of "Without polishing", 25–0 mm of HPS and CS were sieved with 20 mm and 5 mm sieves, and thus obtained 20–5 mm and 5–0 mm of slags were used as coarse and fine aggregates, respectively. In the process of "With polishing", the quality improvement of HPS was attempted with the Los Angeles machine. Firstly, 25–0 mm of HPS was polished in the Los Angeles machine. Secondly, it was sieved with 20 mm and 5 mm sieves, and thus obtained 20–5 mm and 5–0 mm of polished slags were used as coarse and fine aggregates, respectively. In the polishing process, 10 kg of HPS in absolute-dry condition and eight 420 g iron balls were put together into the Los Angeles machine to be rotated 1000 times. It took about for 30 min. From the viewpoint of effective utilization of industrial by-product, it is better to use 25–20 mm of steel-making slags as coarse aggregates. However, to compare the experimental results to the previous studies [8–10], 20–5 mm of steel-making slags were used as coarse aggregates.

The saturated surface-dry density and water-absorption rate of the aggregates were measured in accordance with ASTM C127 [11] and ASTM C128 [12], respectively. Crushing loads were also measured on coarse aggregates. Firstly, each coarse aggregate was dried in an electric furnace at the temperature of 105 degrees Celsius for 24 h. Secondly, it was sieved with 10 mm sieve to be separated into 20–10 mm and 10–5 mm. Thirdly, 100 particles were randomly extracted out of each group, and the mass of each particle was measured. Finally, the peak load, *S* (kN), of each particle under static loading was measured with a pressure-resistance testing machine. Considering the scattering of the experimental data, the representative values of crushing loads were calculated with a statistical method discussed later.

2.3. Mixing method and preparing method of specimen

Coarse aggregate, ground granulated blast-furnace slag, coal fly ash, lime hydrate, and fine aggregate were put into a 2-axis mixer in the above order. After 30 s of dry mixing, water was added, and then additional mixing for 150 s was per-

Table 1
Physical properties of the materials used.

Materials			Specific surface (cm^2/g)		Density (g/cm^3)
Ground granulated blast-furnace slag			4280		2.89
Coal fly ash			4020		2.28
Lime hydrate			–		2.20
Aggregates		Particle size (mm)	Fineness modulus	Saturated surface-dry density (g/cm^3)	Water-absorption rate (%)
Fine aggregate	HPS	5–0	3.64	3.14	7.04
	PHPS	5–0	2.85	3.26	1.67
	CS	5–0	2.82	2.75	7.14
Coarse aggregate	HPS	20–5	6.51	2.75	7.37
	PHPS	20–5	6.49	2.89	2.72
	CS	20–5	6.24	3.35	2.15