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Seven-day test result assessment of the developed strength in composite cement mortar with slag

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HIGHLIGHTS

- The compressive strength at other curing ages estimated from the strength on Day 7 is proposed.
- This model will contribute to the safety assessment of concrete structures during the construction phase.
- The compressive strength increased as the replacement rate of BSSF slag increased.
- The effect of the slag to the strength is significant.

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ABSTRACT

An important research topic for sustainable development is the replacement of natural resources with renewable materials. Several recycled materials, such as furnace slag and steel slag, were used and applied in concrete or cement mortar. The design strength of the concrete or cement mortar normally represents its 28th day strength. Thus, an assessment of the compressive strength of cement mortar with furnace slag powder and steel slag from the early strength is desirable. In this study, Baosteel Slag Short-Flow (BSSF) slag and furnace slag powder were used to replace fine aggregate (0%, 25%, 50%, 75% and 100%) and cement (20%), respectively, through a volumetric method, and three water-binder ratios of 0.45, 0.50, and 0.55 were used to produce composite cement mortar. According to the test results, the compressive strength increased as the replacement rate of BSSF slag increased. Using the test results for the water-binder ratio (W/B) values of 0.45 and 0.55, a hyperbolic function was used to perform a multivariate non-linear regression analysis, thus establishing a compressive strength prediction model for cement mortars of other ages based on the early strength at the age of 7 days. From the confirmatory analysis, at the water-binder ratio W/B = 0.50, the MAPE (mean absolute percentage error) value of the test specimens was found to be 8.12%. Moreover, when the W/B was 0.45 and 0.55, the MAPE value for the test specimens was 9.38% and 5.29%, respectively. All of the MAPE values were less than 10%; thus, the analytical model results established in this study were satisfactory under different conditions. Therefore, the proposed model can be used as a reliable tool for assessing the design strength of cement mortar from early age test results, and it could contribute to the safety assessment of cement mortar structures during the construction phase.

1. Introduction

The construction sector is the second largest carbon dioxide emitter, accounting for approximately 33% of the total global carbon dioxide emission. The aggregates (occupying 55–80% of the concrete volume) have a great influence on the environment and sustainability of structures [1]. Thus, the use of industrial wastes as aggregate and its application in concrete or cement mortar are worth promoting. Steel slag is a by-product of steel production, which accounts for a proportion of approximately 15% by mass of the steel output. Because of its high strength and durability, high bulk density, low abrasion and wear rate, and rough texture, steel slag can be processed to aggregates of high quality comparable with those of natural aggregates; as a result, steel slag aggregates can be used as a construction material. Sas et al. [2] indicated that

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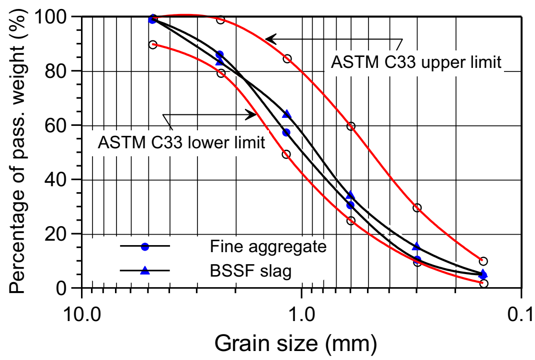

Fig. 1. Cumulative particle distribution of fine aggregate and BSSF slag.

aggregates of steel slag have chemical and mechanical properties comparable to those of similar natural aggregates; thus, aggregates of steel slag can be used in base courses in road structures for motorways and roads with medium traffic loads. In addition, steel slag can also be used to partially replace concrete or pavement materials [2–8]. Xiang et al. [5] investigated the application of cement-free steel slag cementitious material. Four types of steel slag, i.e., hot-spray poured steel slag, hot-stuffing steel slag, Baosteel short-flow (BSSF) steel slag, and wind-quenched steel slag, were used as fine aggregate and a partial replacement of natural sand. In their work, the cementitious material was found to have the characteristics of normal setting time, qualified boiling stability, high early strength, and excellent bending strength. Yu et al. [4] performed a series of tests on concrete made with steel slag and waste glass. Their study showed that the compressive strength and elastic modulus of concrete using steel slag as fine aggregates were 1.33 and 1.32 times those of common concrete, respectively; however, the flexural strength on the 28th day was only 3.2% higher than that of the control mix. This tendency was also found by Qasrawi et al. [6], and the compressive strength of concrete using steel slag as fine aggregates was 1.1–1.3 times that of common concrete.

In Taiwan, basic oxygen furnace slag (BOF), a form of steel slag, has been widely used as backfill material, road construction material, ground improvement materials and other filling materials [9]; however, its volume instability is a very important and a considerably unsafe factor for using steel slag as an aggregate in construction material [7,9]. Solving the volumetric expansion problem of steel slag is vital for slag recycling and reuse. Lee et al. [10] conducted experiments and evaluated 5 commercialized strategies for slag treatments to stabilize the volume of BOF slag. Their study indicated that the hot stage slag modification technique is the most effective method to achieve volumetric stabilization of BOF slag; however, the processing equipment used for this technique is far more expensive than that of the other techniques [10]. Xiao et al. [11] described the BSSF technique, which treats high temperature molten steel slag in a rotating roller body; this technique has the destructive effect of mechanical stress caused by collaborative cooling and rotation of multiple processes, i.e., the high temperature steel slag is cooled by water spray in the roller for quick chilling and fragmentation. As steel and slag have different characteristics (furnace slag molecules have low cohesion), they can be solidified, exfoliated, and separated, and then discharged from the roller body. In the processes of quick chilling and mechanical crushing via the rollers, as the basic oxygen furnace (BOF) slag in the roller body is uniformly in contact with the cooling water, F-CaO and MgO in the BOF slag are fully hydrated and relatively stable; this phenomenon strongly promotes the volume stability of BOF slag. Lee et al. [10] indicated that the residual expansion ratio of BOF slag, with a particle size greater than 5 mm after the roller process, is less than 50% of the original slag; however, this method is less effective than the hot stage slag modification technique, as the volume stability of BOF slag has been effectively enhanced. In addition, the BSSF slag particle size is relatively small and uniform, with 90% of the particles being less than 10 mm, and the roller slag volume expansibility degrades greatly after stabilization; thus, this material is applicable to engineering applications (e.g., asphalt concrete pavement [8,12,13]) and can be used as appropriate earth material [14].

With sustainable development and reuse of waste materials as a starting point, applications involving the additional BSSF slag and furnace slag powder to replace some of the raw materials in concrete or cement mortar constitute a research topic worthy of study. Additionally, the compressive strength at the 28th day is typically used as design strength for structure. Thus, an assessment of the compressive strength of cement mortar with BSSF slag from the early strength is desirable and will be helpful for safety evaluation and analysis of structures under the construction phase. In this study, a series of compressive strength tests are conducted on composite cement mortars with three types of water-binder ratios containing BSSF slag (where the replacement rates of BSSF slag for fine aggregate are 0%, 25%, 50%, 75%, and 100%) and furnace slag powder (the cement is replaced by 20% furnace slag powder). A compressive strength prediction model encompassing such influence factors as the content of BSSF slag and water-binder ratio and the age was proposed.

2. Experiment

2.1. Materials

1. Cement: Type I Portland cement produced by the Taiwan Cement Corporation, the properties of which conform to the Type I Portland cement specified in ASTM C150 [15].
2. Mixing water: Conforms to ASTM C94 [16] concrete mixing water.

Table 2
Chemical properties of the relevant materials. Unit: %.

Properties	Cement	Slag powder	BSSF slag
SiO_2	20.22	33.46	8.76
Al_2O_3	4.96	13.71	1.77
Fe_2O_3	2.83	0.42	29.52
CaO	64.51	42.69	41.67
MgO	2.33	6.21	5.67
SO_3	2.46	1.48	–
LOI	2.4	0.27	2.63
f-CaO	–	–	1.84

Table 1
Physical properties of the relevant materials.

Items	Specific gravity	Water absorption (%)	F.M	Fineness (cm^2/g)
Fine Aggregate	2.63	2.65	2.9	–
BSSF slag	3.22	2.94	3.02	–
Cement	3.15	–	–	3500
Slag Powder	2.8	–	–	4500