Construction and Building Materials 128 (2016) 108–117

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Modelling of the compressive strength development of cement mortar with furnace slag and desulfurization slag from the early strength

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HIGHLIGHTS

- The compressive strength at other curing ages estimated from the early strength on Day 7 is proposed.
- This model can be used for assessing the design strength of concrete during construction phase from early age test results.
- The compressive strength decreased as the replacement rate of desulfurization slag increased.
- The contribution of the slag powder to the strength is significant at later stage.

ARTICLE INFO

Article history:
Received 10 August 2016
Received in revised form 11 October 2016
Accepted 14 October 2016

Keywords:
Cement mortar
Desulfurization slag
Furnace slag
Compressive strength
Prediction model

ABSTRACT

Replacing natural resources with renewable materials is a very important research topic for sustainable development. Several recycled materials such as furnace slag (S) and desulfurization slag (D) were widely used and applied in concrete or cement mortar. The compressive strength at the 28th day was usually used as design strength for structure. Thus, an assessment of the compressive strength of cement mortar with furnace slag and desulfurization slag from the early strength is desirable to develop. In this study, desulfurization slag that could pass through a No. 4 sieve and furnace slag with a fineness of approximately 4000 cm^2/g were used to replace the fine aggregate (0%, 10%, 20% or 40%) and cement (0%, 10%, 20% or 40%), respectively, through a volumetric method. The cement mortar thus formulated was then put through a series of compressive strength tests in which the samples were cured at a 23–25 °C room temperature and a 75 °C high temperature. According to the test results, the compressive strength decreased as the replacement rate of desulfurization slag increased, but increased as that of the furnace slag increased. Using the test results when the replacement rates of D were 0%, 10% and 20%, 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, when the replacement rate of desulfurization slag D = 40%, the MAPE (mean absolute percentage error) value of the test sample cured at high temperature was found to be 6.13%, while that for the test sample cured at room temperature was 11.32%. Moreover, when D was 0%, 10% and 20%, the MAPE value for the test sample cured at high temperature was 3.05%–4.47%, respectively, while that for the test sample cured at room temperature was 7.83%–9.17%. Generally speaking, the results delivered by the analytical model established in this study were satisfactory under different conditions. As it is capable of performing a predictive analysis of the compressive strength of cement mortar at other ages based on the early strength at the age of 7 days, this model could contribute to the safety assessment of concrete structures during the construction phase.

1. Introduction

Desulfurization waste slag (hereafter abbreviated as desulfurization slag, D) is a solid waste generated from the desulfurization process of molten iron in a blast furnace with the help of a desulfurization agent in an integrated steel company that uses iron ore as the main raw material. Currently, the steel companies in Taiwan have an annual production capacity of approximately 300,000 tons of desulfurization slag [1]. Generated in the melting process at high temperature, desulfurization slag is resistant to high temperatures, less affected by climatic changes and very safe because of the low heavy metal mobilization. At present, apart from turning out metallic iron in a magnetic separation process, which is very renewable and valuable, desulfurization slag could be reused, after

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http://dx.doi.org/10.1016/j.conbuildmat.2016.10.083

purification, as an agricultural soil amendment and fertilizer because it meets the standards for defining corrosive industrial wastes in terms of its pH value (as high as 12.5). Given its low heavy metal mobilization, it could also be used as an earthwork backfill material or a partial replacement for limestone in the firing of cement clinker [1]. In recent years, desulfurization slag has been reused to gradually replace the coarse and fine aggregates in some concrete materials and the fine aggregate in cement mortar [1–4]. Kuo and Shu (2014) [2] partly replaced the natural sand in the mixture of cement mortar with desulfurization slag and suggested that the speed of the volume increase of the cement mortar containing desulfurization slag would increase with the replacement rate of desulfurization slag if the mortar was cured at high temperature. The compressive strength tended to decrease as the replacement rate of desulfurization slag increased [3,4]. Blast furnace slag (S), as a raw material for Portland cement, on the other hand, is mainly a byproduct for iron production in an integrated steel company. According to how it is cooled, it could be divided into water-cooled and air-cooled furnace slags. Water-cooled furnace slag, once ground into fine powder, is usually called slag powder and could be mixed into concrete to replace some cement. This could not only reduce the cost of the concrete but also improve its quality [5]. According to Lho et al. (2012) [6], when slag powder replaces part of the cement, the compressive strength and tensile strength would first increase with the replacement rate of the furnace slag. However, when the replacement rate of furnace slag surpassed 40%, the compressive strength and tensile strength would decrease instead.

With sustainable development and the reuse of waste materials as a starting point, applications involving the addition of desulfurization slag and slag powder to replace some of the raw materials for concrete or cement mortar therefore constitute a research topic worthy of study. Additionally, the compressive strength at the 28th day was usually used as design strength for structure. Thus, an assessment of the compressive strength of cement mortar with furnace slag and desulfurization slag from the early strength is desirable developed, it will be very helpful to the safety assessment and analysis of structures under construction. In this study, a series of compressive strength tests were carried out on cement mortars with a fixed water-binder ratio containing desulfurization slag and furnace slag (when the replacement rates of desulfurization slag with fine aggregate D are 0%, 10% and 20%), and a compressive strength prediction model encompassing such influence factors as the contents of desulfurization slag and slag powder and the age was proposed. A compressive strength test was then conducted under a different replacement rate (D = 40%) to validate the compressive strength prediction model established in this study.

2. Test program

2.1. Test materials

1. Cement: Type I Portland cement produced by the Taiwan Cement Corporation was used; its properties conformed to those of Type I Portland cement specified in ASTM C150.
2. Mixing water: Conforms to ASTM C94 for concrete mixing water.
3. Fine aggregate: The aggregate originated from the Ligang District and conformed to ASTM C33.
4. Furnace Slag (S): GGBFS (Ground-granulated blast-furnace slag) was produced by the CHC Resources Corporation and was ground to 4000 cm^2/g, and its properties conformed to ASTM C989.
5. Desulfurization slag (D): Desulfurization slag is the surplus remaining after the purification of the GGBFS produced by an integrated steel plant using magnetic separation. The slag passed through a No. 4 sieve as fine aggregate.

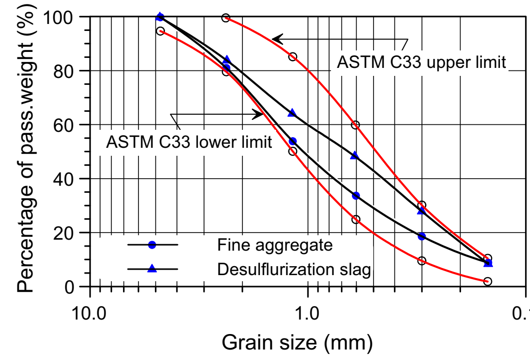

Fig. 1. Cumulative particles distribution of fine aggregate and desulfurization slag.

The particle size distribution curves of the fine aggregate and desulfurization slag are shown in Fig. 1.

2.2. Test variables and method

This study used a standard mix design of cement mortar according to ASTM C109, with a fixed water-binder-fine aggregate ratio of 0.5:1:2.75. The volumetric method was used for the design. Recycled materials of slag powder and desulfurization slag were used to replace the cement (0%, 10%, 20% and 40%) and fine aggregate (0%, 10%, 20% and 40%), respectively. A 5 cm * 5 cm * 5 cm cement mortar specimen was cast and solidified. The forms were removed after 24 h, and the specimens were placed and cured at room temperature (23–25 °C) and high temperature (75 °C) in saturated limewater, respectively. The flow and setting time were tested in accordance with ASTM C230 and ASTM C403, respectively. The compressive strength was tested at the ages of 3, 7, 28, 56 and 91 days according to ASTM C109 and ASTM C597.

The physical properties of the materials are as shown in Table 1, and the chemical properties of the materials are as shown in Table 2. The unit weights of the mix design cement mortar with added recycled materials are as shown in Table 3.

Table 1
The physical properties of materials.

Properties	Specific gravity	Unit weight (kg/m^3)	Water absorption (%)
Fine Aggregate	2.63	1865	1.6
Desulfurization Slag	2.38	1009	34

Table 2
The chemical properties of the materials. Unit:%.

Properties	Cement	Slag Powder	Desulfurization Slag
SiO_2	20.22	34.47	9.93
Al_2O_3	4.96	13.71	4.22
Fe_2O_3	2.83	0.33	8.23
CaO	64.51	41.00	69.08
MgO	2.33	6.60	2.33
SO_3	2.46	–	4.3
Alkalis	0.48	–	–
K_2O	–	–	0.06
Na_2O	–	–	0.14
TiO_2	–	–	–
P_2O_5	–	–	0.17
MnO	–	–	0.6
Cr_2O_3	–	–	0.08
LOI	2.4	3.1	–
f-CaO	–	–	0.95