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Effects of sulfate rich solid waste activator on engineering properties and durability of modified high volume fly ash cement based SCC

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ABSTRACT

The engineering properties and durability of high volume low calcium fly ash (HVFA) cement based self-compacting concrete (SCC) modified with addition of circulating fluidized bed combustion (CFBC) fly ash were explored. Experimental results showed that an addition of CFBC fly ash did not influence the stability and passing and filling abilities of modified HVFA cement based SCCs. But its presence significantly improved the compressive strength, bonding behavior, and durability of the hardened SCC specimens. The added small amount of CFBC fly ash was found to increase the earlier compressive strength of hardened SCC specimen at one day of curing up to 43.8% higher than that of the control SCC specimen, which indicates a remarkable contribution of CFBC fly ash addition to shortening the time of construction. At ages of 3, 7, and 28 days, such increases were up to 30.2%, 22.3%, and 17.8%, respectively.

1. Introduction

Nowadays, the modern cement factories have been under intense pressure to reduce the environmental impacts of their products and operations. Therefore, the sustainable development principle has become the most critical issue in the cement industry. In general, the sustainable manufacture of cement has been defined as the creating process of manufactured products during which the negative effects on environmental impacts and the consumptions of applied energy, human labor, and natural resources are minimized [1,2].

According to the definitions, sustainable manufacturing must address the integration of all the three indicators of environmental, social, and economic considerations, known as the triple bottom lines of sustainability. Sustainable achievement in accordance with economical challenge to obtain cost-effective environmentally friendly building products has been defined as a development of manufacturing process producing the resulting products with high potential of competitiveness through time. In accordance to environmental challenge, the sustainable development has to be responsible for the consideration of minimizing the use of non-renewable natural resources and reducing/eliminating the environmental impact. Also, the sustainable achievement in accordance with the social challenge has been related to the promotion of both developed society and improved human life quality associated with the renewed quality of wealth and jobs. Currently, it has been apparently to accept that sustainable development for cement manufacture has to be evaluated based on not only the individual triple bottom lines of economic, environmental, and social performance but also to consider their interdependencies and costs [3–5].

High volume low calcium fly ash (HVFA) concrete is one of the most promising candidates for achieving the sustainability development of concrete industry because it significantly cuts the CO_2 emission per unit volume of concrete as compared with the conventional plain ordinary Portland cement (OPC) concrete [4]. Normally, the HVFA cementing binders are fabricated by very high quantity of low calcium fly ash (at least 50% by weight) as partial replacement for OPC so that they have been widely applied for constructing fields without crucial requirements for high mechanical properties [6,7]. By using low water to binder ratio (W/B) and high amount of superplasticizer (SP), the Canada Centre for Mineral and Energy Technology (CANMET) paved the promising way for manufacturing high performance HVFA cement concrete qualifying most requirements of various kinds of construction because of its mostly satisfactory engineering and durability performance [6–15]. However, the emerged impacts of applying the HVFA cements for construction materials are the prolonged setting properties and decreases in both early and long-term compressive strengths [7,12,16,17]. Therefore, the pretreated fly ash by mechanical grinding, applying accelerated curing, or addition of mineral or chemical activator has widely adapted for fresh HVFA cement [17–24]. In jobsite

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application, the chemical activation with gypsum/anhydrite ($CaSO_4 \cdot 2H_2O/CaSO_4$) [25] has been the most preferable technique instead of using either sodium sulfate (Na_2SO_4) or commercial strong alkaline [25–29] due to requirements for safety and economy.

During the past decades, the power demand for human life has been significantly dependent on power generation from the pulverized coal combustion which can accelerate the issues on environmental pollution and climate change. Recently, the requirement for clean power generation has led to the annual replacement of the traditional coal combustion by a new burning technique such as the circulating fluidized bed combustion (CFBC) process which significantly contributes to the reduction of the SO_2 and NO_x emission through the reactions of these gases with added phases of CaO from calcium rich raw materials (such as limestone or dolomite) as absorbents during the burning process [30,31]. Therefore, anhydrous anhydrite ($CaSO_4$) is formed in residual solid waste, i.e., the CFBC ashes, causing its physical and chemical properties different from those of traditional coal fly ashes. Such the high free lime (f-CaO) from the unreacted absorbent and the anhydrite ($CaSO_4$) limit the utilization of CFBC ashes due to the expansion concern by ettringite (AFt) formation [32]. Therefore, CFBC ashes significantly contribute to the annually increased solid wastes with sulfur, possibly leading to the pollutions in air due to the ashes and on surface water due to the high alkalis.

The utilization of the sulfur rich solid wastes such as CFBC fly ash in cement/concrete industry, particularly in HVFA cement concretes seems to be one of the most efficient ways to mitigate the aforementioned impacts due to the dual benefits, i.e., both the issue of environmental pollution caused by alkali-sulfate rich CFBC fly ash and the cost of resultant concretes are reduced. However, such interesting goal has not been established. The current study aims at estimating the effect of the CFBC fly ash addition to partially substitute for low calcium Class F fly ash on the enhanced engineering properties and durability of modified HVFA cement based SCC. The crucial contribution of the current study is not only to initially propose an innovative utilization of CFBC fly ashes as admixture additive in the modified HVFA cement concrete leading to significant reductions of concrete cost [4,33–35] and sulfate rich waste discharge, but also to propose an innovative way to enhance the application of HVFA concrete with satisfactory early mechanical properties and high later engineering and durability properties. In Taiwan, the approximate costs of bulk cement and raw fine/coarse aggregate are about 100 USD/ton and 14.5 USD/ton, respectively. The costs for both the circulating fluidized bed combustion fly ash (CFA) and low calcium Class F fly ash (FFA) are about 20 USD/ton. The market price of ready-mixed concrete with 28-day compressive strength of 60 MPa is about 100 USD per cubic meter of fresh concrete. In current study, half of 530 kg/m^3 cement was replaced by CFA/FFA in the HVFA cement concrete which reduced about 21.2% of the price of 100 USD per cubic meter of ready-mixed concrete.

2. Experimental program

2.1. Materials and mix proportions

In this study, Type I ordinary Portland cement (OPC) accordant to ASTM C150, low calcium Class F fly ash (FFA), circulating fluidized bed combustion (CFBC) fly ash (CFA), and commercial gypsum were used to produce cementing mixtures. The physicochemical properties and analysis for mineralization of these materials were detailed in Table 1 and Fig. 1, respectively. Accordingly, the Class F fly ash mainly comprises crystals of mullite and quartz. On the other hand, the CFBC fly ash mostly comprises anhydrite, free lime (f-CaO), and portlandite. In this study, the coarse and fine aggregates were the natural crushed stone with maximum size of 20 mm and specific gravity of 2.65 and the river sand with fineness modulus (FM) of 2.9 and specific gravity of 2.67, respectively. Water absorptions of the river sand and natural crushed stone were 1.0% and 0.8%, respectively. To produce SCC with good bonding between binding matrix and aggregates, both the sand and stone were carefully washed before being used. In this study, the workability of the fresh SCCs was controlled by using Type G superplasticizer (SP). To produce the reinforced concrete specimens for the pull-out test, the deformed commercial steel rebars with diameter of 16 mm were used. The nominal yield strength of the steel rebars used in this study was 420 MPa.

To completely estimate the effect of the CFBC fly ash (CFA) on the engineering behaviors of the high volume low calcium fly ash (HVFA) cement paste and concrete with reduced laboratory work, the experimental program was separated into two steps. The first step was established to optimize the addition of CFA amount to achieve the modified HVFA cement paste with highest compressive strength. During the first step, the reference HVFA cement paste (Control mix)

Table 1
Physical properties and chemical compositions of raw materials.

	Portland cement (OPC)	Class F fly ash (FFA)	CFBC fly ash[a] (CFA)
Specific gravity	3.15	2.17	2.70
Blaine fineness, cm^2/g	3450	2630	3000
SiO_2, wt%	20.42	58.33	5.22
Al_2O_3, wt%	4.95	26.23	2.21
Fe_2O_3, wt%	3.09	3.49	0.58
CaO, wt%	61.96	5.72	56.80
MgO, wt%	3.29	1.26	2.06
SO_3, wt%	2.40	–	32.40
Na_2O, wt%	–	0.27	–
K_2O, wt%	–	0.48	–
TiO_2, wt%	–	1.46	–
L.O.I, wt%	1.75	2.76	–

[a] Industrial by-product of desulfurization process with a large amount of retained calcium sulfate.

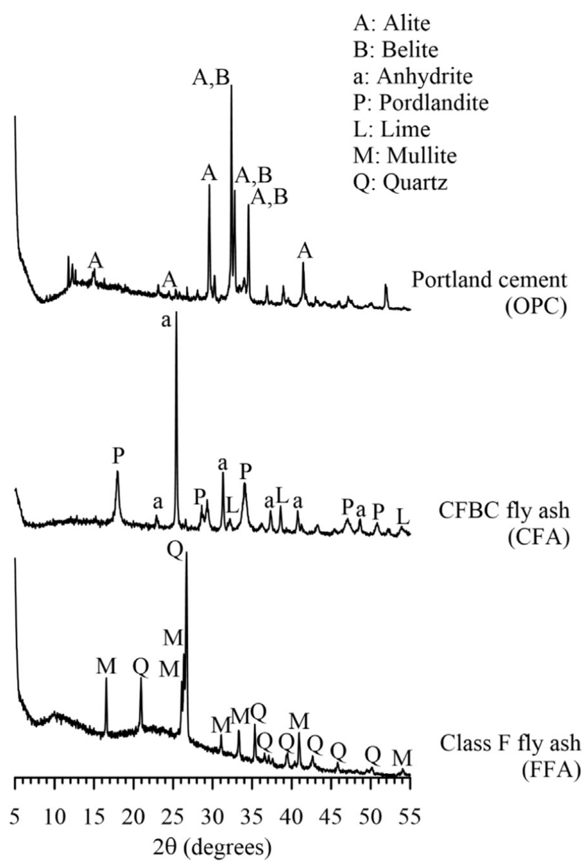

Fig. 1. XRD patterns of raw materials.