Physical and Mechanical Properties of Concrete with Circulated Fluidized Bed Combustion Fly Ash, Ground Granulated Blast Furnace Slag and Coal Fly Ash

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Abstract. This study explores the physical and mechanical properties of concrete with circulated fluidized bed combustion (CFBC) fly ash, ground granulated blast furnace slag (GGBFS) and coal fly ash. Five different blended cements were prepared to cast concrete specimens and the slump, unit weight (density), compressive strength, length change of blended cement concrete were measured. Tests show that the specimens with coal fly ash have better workability. Meanwhile, the replacement of cement by CFBC fly ash, GGBFS, and coal fly ash lead to reduce the unit weight, compressive strength and length change of concrete. The concrete specimen with the replacement of cement by CFBC fly ash of 10%, GGBFS of 10%, and coal fly ash of 10% was recommended based on the present results.

Introduction

Reduction of Portland cement quantity in traditional concrete has been an interesting and important topic motivated by environmental, economic, and technical requirements. Circulating fluidized bed combustion (CFBC) is a very attractive environmental-friendly coal-combustion technology for coal burning and lower SO_2 and NO_x emissions [1, 2]. CFBC fly ashes are different from traditional coal-fired fly ashes for good pozzolanic and hydraulic properties. It is richer in anhydrite, free lime, relatively low SiO_2 and Al_2O_3 contents, large specific surface area, and high water requirement [3, 4]. Coal fly ash and ground granulated blast furnace slag (GGBFS) are two types of solid waste materials. Both are calcium aluminosilicate glasses but their reaction products are quite different. Coal fly ash and GGBFS are widely utilized in cement as the admixtures. These binders are characterized by their superior durability performance and low environmental impact [5-7]. However, there are only a few investigations of the use of CFBC fly ash in cement as an admixture. Chen et al. [8] found that the most reasonable dosages of CFBC fly ash were 70% and the finer CFBC fly ash is better to improve the compressive strength. Sheng et al. [9] pointed out that the CFBC fly ash had a little effect on the compressive strength when its content was below 20%. Chi and Huang[10] reported that CFBC fly ash has a positive effect on compressive strength, splitting tensile strength, and sulphate attack resistance of hardened roller compacted concrete. Zhang and Qiu [11]have manufactured the cement with CFBC fly ash and PFA which can attain about 32.5 to 42.5 MPa of compressive strength at 28 days. Zhang et al. [1] found that the use of CFBC fly ash (usually over 5% SO_3 by weight) in concrete would result in a great risk of destructive expansion. In this study, CFBC fly ash, GGBFS and coal fly ash were used in Portland cement to investigate the physical and mechanical properties of blended cement concrete.

Experimental program

Materials. Four kinds of materials, Type I ordinary Portland cement (OPC) conforming to ASTM C150, circulated fluidized bed combustion (CFBC) fly ash, ground granulated blast furnace slag (GGBFS) and Class F coal fly ash with the physical properties and chemical compositions of these materials listed in **Table 1** were used in this study. CFBC fly ash and coal fly ash were obtained from the Mailiao Six Light Naphtha Cracker Plant, located in the Yunlin county of Taiwan, and GGBFS supplied by CHC Resources Corporation, Taiwan. CFBC fly ash of gray-and-white powder passing No. 200 (75μm) accounts for about 86% of the particles. The specific gravity of CFBC fly ash is 2.75 - 2.85. The blaine specific surface area was 2880~3050 cm^2/g. Coal-fired fly ash and GGBFS were used for partial cement replacement by weight. The specific gravity of coal-fired fly ash is 2.39. The blaine specific surface area was 4050 cm^2/g. The specific gravity of GGBFS is 2.88. The blaine specific surface area was 6000 cm^2/g. River sand with its fineness modulus, bulk density and absorption of 2.33, 2580 kg/m^3 and 2.94%, respectively, was used as a fine aggregate. Coarse aggregate had a fineness modulus of 6.48, a bulk density of 2540kg/m^3, and an absorption of 0.83%.

Table 1 Physical properties and chemical composition of raw materials (%wt)

Chemical compositions (%)	OPC	CFBC fly ash	GGBFS	Coal fly ash
Specific gravity	3.15	2.76	2.88	2.39
Blaine fineness, cm^2/g	3450	3000	6000	2370
Calcium oxide, CaO	63.8	56.80	40.67	1.94
Sulfur trioxide, SO_3	2.20	32.40	0.56	0.57
Silicon dioxide, SiO_2	20.6	5.22	34.58	56.66
Ferric oxide, Fe_2O_3	3.20	0.58	0.44	7.56
Aluminum oxide, Al_2O_3	5.40	2.21	13.69	23.97
Magnesium oxide, MgO	1.98	2.06	7.05	0.93
Loss on ignition, L.O.I.	1.00	7.83	4.72	2.76

Mixes design and specimens preparation. Mixing of Ordinary Portland cement (OPC) concrete and blended cement concrete with 393 kg of binder per cubic meter according to ASTM C 192 was designed. The liquid/binder ratio was kept at a constant of 0.5. Five different blended cements were prepared with varying proportions of OPC, CFBC fly ash, GGBFS, and coal fly ash to produce concrete specimens. The mix proportions are shown in **Table 2.** The specimens were cast and kept in steel molds for 24 hours, and then they were demolded and moved into a curing room at relative humidity of 80% RH and 25℃ until testing. The specimens were tested in triplicate sets until the time of testing.

Table 2 Mix proportions of the blended cement concrete specimens

Mix no.*	Cement/ CFBC fly ash/ GGBFS/ Coal fly ash (mass ratio)	Water (kg/m^3)	Cement (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	CFBC fly ash (kg/m^3)	GGBFS (kg/m^3)	Coal fly ash (kg/m^3)
OPC	10/0/0/0	196	393	1046	662	---	---	---
C1G0F0	9/1/0/0	196	354	1046	659	39	---	---
C2G4F0	4/2/4/0	196	157	1046	642	78	157	---
C1G1F1	7/1/1/1	196	275	1046	647	39	39	39
C1G2F2	5/1/2/2	196	197	1046	631	39	78	78

* Within mixture designation CxGyFz, x represents the level of replacement (in wt%) of CFBC fly ash, y represents the level of replacement (in wt%) of GGBFS and z represents the level of replacement (in wt%) of coal fly ash as cement.

Methods. This study is to investigate the physical and mechanical properties of concrete with circulated fluidized bed combustion fly ash, ground granulated blast furnace slag and coal fly ash.

Slump test. Slump test used to determine the workability of fresh concrete was conducted according to the ASTM C143-12.

Unit weight test. The unit weight (density) of concrete was conducted according to the ASTM C138-14. The unit weight is determined by the formula: $D = (M_c – M_m) / V_m$, where M_c is the weight of the measure holding the concrete, M_m is the weight of the empty concrete measure (base of air meter), and V_m is the volume of the measure.

Compressive strength test. The compressive strength test of the concrete was conducted according to ASTM C39-15.

Length change test. The length change test was done in accordance with ASTM C596-09. The length of the shrinkage specimens (L_x) was measured at the ages of 3, 7, 14, and 28 day, respectively. The length change was then calculated by the following formula: LC (%) = $[(L_i - L_x)/G] \times 100\%$, where L_i is the the initial length and G is the nominal effective length.

Results and discussion

Slump and unit weight. The slump and unit weight of the blended cement concrete specimens are given in **Table 3.** It can be seen that the slump of OPC concrete specimen is 15 cm, whereas 17, 20 and 18 cm for specimens C1G0F0, C1G1F1 and C1G2F2, which are higher than OPC, respectively. The specimens with coal fly ash have better workability because of the spherical shape of coal fly ash particles. Due to their spherical shape, fly ash particles reduce the internal friction between the ingredients of concrete and this in turn results in a considerable increase in fluidity of the concrete mix. Specimen (C2G4F0) has the lowest slump of 10 cm. This may be attributed to the high-percentage replacement of cement with 20% CFBC fly ash and 40% GGBFS. The specific surface area of GGBFS is rather large with respect to cement and hence a great amount of water is needed to feed up hydration reactions. The unit weight of OPC concrete specimen is higher than those of any others due to its higher specific gravity. It indicates that the unit weight of concrete is totally related to the specific gravity of raw materials. Specimen (C1G2F2) has the least unit weight of concrete due to more replacement of cement with coal fly ash which has the least specific gravity.

Table 3 Slump and unit weight of the blended cement concrete specimens

Mix. no.	Slump (cm)	Unit weight (kg/m^3)
OPC	15	2213
C1G0F0	17	2194
C2G4F0	10	2159
C1G1F1	20	2118
C1G2F2	18	2102

Compressive strength. The compressive strengths of OPC and blended cement concrete specimens at the ages of 7 and 28 curing days are shown in **Figure 1.** It can be seen that OPC concrete specimen has the highest compressive strength than any others. Meanwhile, the compressive strength of concrete at 28 days is higher than that at 7 days. At the age of 28 days, OPC concrete has the highest compressive strength, with 42.0 MPa of the compressive strength, followed the specimen C1G1F1 and specimen C2G4F0, with 40.7 MPa and 38.4 MPa, and then the specimen C1G2F2, with 34.2 MPa. Specimen C1G0F0 is on the other end of the scale, with 32.0 MPa. The compressive strength is affected by the cementitious materials, in particular the content of cement. The decrease in compressive strength for blended cement concrete is due to the reduction of the cement content in the mixture and too much $Ca(OH)_2$ produced from the reaction of free lime with water which is unfavorable to the mechanical properties of cement. With the fixed CFBC fly ash of 10%, the specimen with GGBFS of 10% and coal fly ash of 10% (C1G1F1) had the highest compressive strength at 28 days. The specimen with higher (C1G2F2) or lower (C1G0F0) amount of GGBFS and fly ash showed the lower compressive strength at 28 days. Thus, 10% cement replacement for each cementitious material could be regarded as the optimum range. The concrete specimen with the replacement of cement by CFBC fly ash of 10%, GGBFS of 10%, and coal fly ash of 10% was recommended based on the present results.

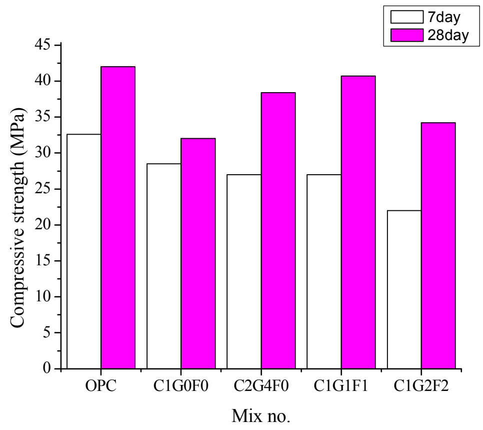

Figure 1 Compressive strength of concrete ages of 7 and 28 days

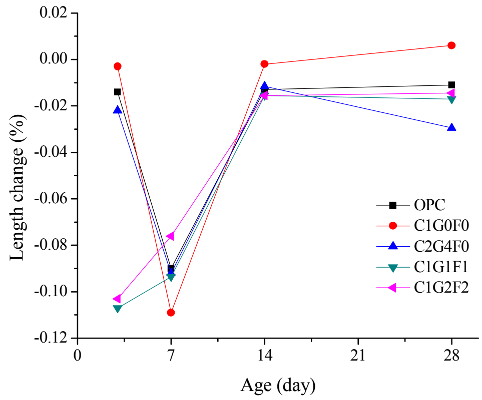

Figure 2 Length change of concrete at the ages of 3,7, 14 and 28 days

Length change test. Length change is an important technical parameter influencing structural properties and durability of the material. The length change or drying shrinkage of OPC and blended cement concrete at the ages of 3, 7, 14 and 21 curing days is shown in Figure 2. The length change of OPC concrete decreases at the beginning of 3 days. The fall lasted for 7 days and then began to increase to the age of 14 days and continued to rise slightly or level off till the age of 28 days. The trend of length change for specimen C1G0F0 is similar to that of OPC concrete. It should be noted that the length change of C1G0F0 was positive at 28 days. It indicates that the length change of C1G0F0 swelled at the age of 28 days. The replacement of cement by CFBC fly ash, GGBFS and coal fly ash decreases the length change at the age of 28 days due to their finer particle sizes which can fill the pore and result in lower length change for blended cement concrete.

Conclusions

This study investigates the physical and mechanical properties of concrete with circulated fluidized bed combustion (CFBC) fly ash, ground granulated blast furnace slag (GGBFS) and coal fly ash. On the basis of test results, the following conclusions should be drawn:

(1) OPC concrete has the higher unit weight and compressive strength than any others.

(2) The replacement of cement by CFBC fly ash, GGBFS, and coal fly ash lead to reduce the length change of concrete at the age of 28 days. The concrete specimen with replacement of cement by CFBC fly ash of 10%, GGBFS of 10%, and coal fly ash of 10% was recommended based on the present results.

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