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Strengths development of slag-based paste with CFBC fly ash under different curing conditions

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ABSTRACT

The mechanical properties of hardened no-cement paste incorporated with utilization of circulating fluidized bed combustion (CFBC) fly ash, ground granulated blast furnace slag (GGBFS), and class F fly ash (FA) was investigated. The ratios of slag replacement by class F fly ash were 0, 0.2, and 0.5 with CFBC fly ash additions of 15% and 20% using water-to-binder ratio of 0.35. Curing conditions introduced as the specimens were cured at 20 °C, 30 °C, and 40 °C, respectively as initial curing condition, thus after 3 days, the specimens were subjected to the constant temperature of 20 °C. The result showed that curing in the high temperature tended to increase the strength and the addition of CFBC fly ash by 20% was chosen as the optimum amount to improve the compressive strength for later ages at higher temperature.

1. INTRODUCTION

Consistently there have been many efforts from some researchers in the construction field due to the major concern over environmental problem related to global warming. Portland cement is the major problem due to the production in the large amount releases lot of carbon dioxide (CO_2) emissions. Thus, some researchers pay more attention to utilize the power plant residue such as fly ash owing to this residue can be classified as environmental-friendly material. Ground granulated blast furnace slag (S) and class F fly ash (F) were the most trendy pozzolanic material that can be used to partially replace ordinary Portland cement for the reason that these materials can improve the mechanical and durability properties of paste, mortar and/or concrete. Apparently, many researchers developed the recent waste material from the thermal power plant by using circulating fluidized bed combustion (CFBC) technology. This technology releases a lot of fly ashes that have good physicochemical properties. Reducing the SO_2 and NO_x emissions is the main purpose of the application of the aforementioned method. The CFBC fly ash (C) mostly has the non-spherical form and contains high CaO and SO_3 content. When the CFBC fly ash dissolves with the water,

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the environment will become alkaline which have an advantage for the presence of slag in the mixture to activate the slag with the major hydration products consist of ettringite (AFt), portlandite, calcite ($CaCO_3$), and amorphous calcium silicate hydrate (C–S–H / C–A–S–H) gel (Chen 2015; Nguyen 2014; Nguyen 2015; Nguyen 2016).

The utilization of CFBC fly ash as an additional pozzolanic material is promising method for improving the engineering properties of slag-based materials. (Chen 2015) studied the mix proportions of SFC binder pastes to obtain the long term compressive strength. It was found that approximately the 28-day compressive strength of 68 MPa was achieved by using 30% class F fly ash with 20% CFBC content. The similar result was also obtained by adjusting the class F fly ash content to 10% and 15% CFBC fly ash content. Thus, the best compressive strength can be achieved using the optimum range of 15–20 wt.% CFBC fly ash and 10–30 wt.% fly ash regardless the curing condition. (Nguyen 2014; Nguyen 2015) found that improvement of sulfate resistance was observed in producing mortar composed both of slag and CFBC fly ash. Furthermore, the SFC binder has been applied to create high-strength self-compacting concrete in the range of 41.8–65.6 MPa at age of 28 days can be produced with fly ash content up to 50 wt.% (Nguyen 2016). In the other hand, (Nguyen 2015) reported presence of CFBC fly ash (2.5–5 wt.%) in the modified high volume fly ash (HVFA) cement pastes is effective to enhance the compressive strength with the increment up to 23.1% at 28 days. The use of CFBC fly ash in the production of control low strength material (CLSM) was investigated in the previous study conducted by (Park 2017). (Chi 2016) stated the more OPC replacement by CFBC fly ash, the less the compressive strength of mortars with blended cement and the recommended amount of the amount of ordinary Portland cement (OPC) replacement by CFBC fly ash and GGBFS was recommended to be limited below 20% and 70%, respectively.

The curing condition affects the structure integrity of specimens due to the higher curing temperature resulted in higher strength at early ages owing to the hydration rate was rapid undoubtedly. (Fan 2017) investigated the mechanical properties of ceramsite concrete subjected to various elevated temperatures up to 60 °C. It showed that early age highest compressive strengths was achieved at 60 °C around 14 MPa but the concrete cured at 20 °C had the best strength in the later curing age approximately 25 MPa. (Aprianti 2016) conducted the experimental research using high volume cementitious materials with four kind of curing conditions. The results revealed that the strengths of the mortar cured in hot air curing increased 14% compared with mortar cured in hot water curing. In general, the main objective of this study is to determine the effect of different curing conditions on the compressive strength of ternary eco-binder paste made with slag, class F fly ash and CFBC fly ash. In addition, the pH value and X-ray diffraction (XRD) have been used to determine the material characteristic and the hydration product of the SFC paste.

2. EXPERIMENTAL PROGRAM

2.1 Materials

Ground granulated blast furnace slag (S), class F fly ash (FFA) (F), and CFBC fly ash (C) were used as a binder in this present study. Their chemical components are presented in Table 1. It showed that CFBC fly ash mostly composed of CaO and SO_3, whereas GGBFS mostly includes CaO and SiO_2 and high content of SiO_2 was discovered in class F fly ash. The specific gravity of slag, class F fly ash, and CFBC fly ash are 2.90, 2.26, and 2.70, respectively. The Blaine fineness of slag was 6000 cm^2/g, whereas CFBC fly ash was 3000 cm^2/g.

Table 1. Chemical composition of the material

	GGBFS	CFBC fly ash	Class F fly ash
SiO_2, %	34.86	5.22	61.10
Al_2O_3, %	13.52	2.21	18.00
Fe_2O_3, %	0.52	0.58	6.93
CaO, %	41.77	56.80	3.82
MgO, %	7.18	2.06	1.33
SO_3, %	1.74	32.40	0.40
K_2O, %	-	-	1.14
Na_2O, %	-	-	1.33
TiO_2, %	-	-	0.71
L.O.I, %	4.27	-	2.76

2.2 Mixture proportion and specimen preparation

Total of 6 different mixtures were prepared to observe the behavior of hardened paste. The mix proportions of the following ternary blended eco-binder paste were listed in Table 2. The binders were prepared by replacing the slag with 0%, 20%, and 50% by weight of class F fly ash. Considering the optimum range of CFBC fly ash proposed by (Chen 2015), the CFBC fly ash content was added into the mixture with the fixed amount at 15% and 20% by total weight of slag and class F fly ash. The water-to-binder ratio was fixed at 0.35. For example, the mix C15S8F2 consists of 80% slag and 20% class F fly ash with addition 15% CFBC fly ash. For this particular work, the mixtures were casted into 50 mm cubes and sealed in order to prevent the water loss due to evaporation. After 24 h, the specimens were removed from the mould and cured into the curing chamber to maintain the stable condition.

Table 2. Mixture proportions of paste (unit: kg/m^3)

Mixture	CFBC fly ash	Slag	Class F fly ash	Water
C15S10	186.83	1245.51	-	501.32
C15S8F2	182.39	972.75	243.19	489.41
C15S5F5	176.12	587.06	587.06	472.58
C20S10	238.41	1192.03	-	500.65
C20S8F2	232.98	931.93	232.98	489.26
C20S5F5	225.29	563.24	563.24	473.12

2.3 Curing conditions

Curing chamber with controlled temperature and humidity is used for curing the specimens. After demoulding, all specimens from various mixes are immediately exposed to three initial curing schemes. The initial curing condition is the specimens are cured with the temperatures of 20 °C, 30 °C, and 40 °C, respectively for 3 days (denoted as T20, T30, and T40). Thus, after initial condition is fulfilled, the specimens are cured in the same chamber into the constant temperature of 20 °C until the testing day.

2.4 Testing program

The compressive strength tests were carried out using a uniaxial compression testing machine in accordance with ASTM C109. The compressive strengths for all specimens were conducted at 3, 7, 14, and 28 days. In addition, the relative humidity of curing chamber was constantly fixed at 65% for all curing schemes. The pieces of broken specimen that crushed from the compressive strength test were collected and soaked in alcohol to stop hydration process in order to analyze the hydration products which examined by X-ray diffraction (XRD) using D2-Phaser X-ray Diffractometer. pH meter has been used to measure the pH value in order to ensure the alkaline environment that caused by addition CFBC fly ash.

3. RESULTS AND DISCUSSIONS

3.1 pH measurement

As mentioned before, when the CFBC fly ash diluted with water, the environment became alkaline. This phenomenon was proved by the examination generated by mixing various CFBC fly ash contents into the fixed amount of water. Fig. 1 shows the effect of CFBC fly ash addition against the pH value. It showed that when CFBC fly ash amount was added into the water, the pH increased dramatically. Even the addition of 1% CFBC fly ash, the pH reached 11.90. The pH values were stable approximately at 12.85 when the CFBC fly ash content was above 5%. (Chang 2002) mentioned that the higher the pH value, the better slag hydration capacity activation. Also, (Zhou 1993) reported that the pH value is the main factor affecting the hydration of alkali activated slag.

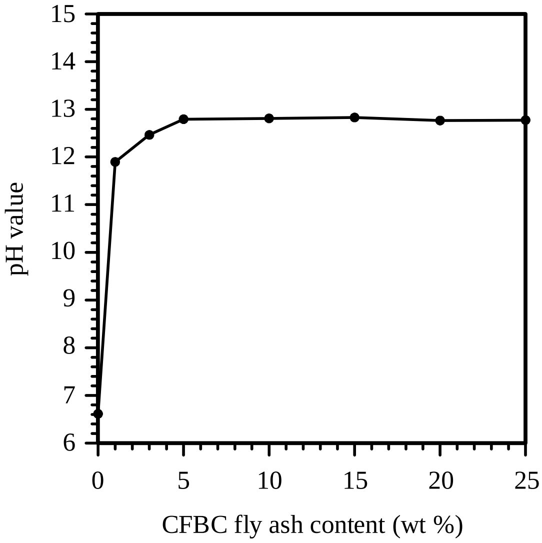

Fig. 1 pH values for various amount of CFBC fly ash

3.2 Compressive strengths

Fig. 2 shows the compressive strengths development of hardened paste after cured in the three different initial curing conditions of 20 °C, 30 °C, and 40 °C during 3 days which denoted as T20, T30, and T40. It is observed that there is an increase in the compressive strength of paste cured at elevated temperatures for 3 days, and the increment was even higher at 40 °C. The results indicate that the initial curing condition greatly affects the paste strength both for early and later ages. Generally, the higher curing temperature resulted in higher compressive strength due to faster reaction rate that produced lot of hydration products related with microstructural changes. Mix C15S8F2 exhibits a considerable strength improvement at 28 days by 37.75% and 61.97% at initial curing temperature of 30 °C and 40 °C, respectively compared with the strength at 20 °C. Mixture with the 100% content of slag shows the highest compressive strength by 33.15, 36.91, and 41.84 MPa at initial curing conditions of 20 °C, 30 °C, and 40 °C, respectively. However, the reduction in compressive strength is occurred with the slag replacement content.

As shown in Fig. 2(a), the slag replacement by fly ash in the amount of 20% and 50% resulted in the strength reduction of 23.77% and 31.64% at 28 days. Similar behaviors in strength reduction are observed with different curing schemes. In Fig. 2(b), at 30 °C, the reductions were calculated with the values of 5.69% and 29.37% for mixes C15S8F2 and C15S5F5. Moreover, when the slag contents are 80% and 50%, the similar trend is observed with the reduction strengths of 2.17% and 17.61% compared with the mix with 100% slag content at initial temperature of 40 °C as mentioned in Fig. 2(c). Apparently it appears that the increase of slag replacement by fly ash generates the lower quality of paste due to the compressive strength decreases simultaneously. The influences of CFBC fly ash content on the compressive strength with various initial curing conditions are presented in Fig. 3. At ambient temperature of 20 °C, mixes S10 and S5F5 showed reduction of strength when CFBC fly ash was added from 15% to 20%. In contrast, the compressive strength of S8F2 mixture was increased by 12.55% when the CFBC fly ash amount was raised by 5%. When the initial curing temperature was elevated and the amount CFBC fly ash was substituted by 20%, mix S10 showed significant improvement on the strength. The increments were shown at 8.02% and 3.94% for T30 and T40, respectively. The highest compressive strength of 43.49 MPa was obtained by mix C20S10 at 40 °C. Furthermore, a fall in compressive strength with the rise of temperature is observed when slag replacement is applied. Slag replacement in the amount of 20% and 50% by fly ash exhibited the strength reduction due to substitution CFBC fly ash from 15% to 20% up to 28.20%. In general, regardless the rise of elevated temperature, the better compressive strength is achieved when CFBC fly ash is utilized in the amount of 20% by the weight of slag and class F fly ash. Some studies conducted by (Chen 2015) confirmed that the utilization of CFBC fly ash by 20% can improve the compressive strength at the later ages.

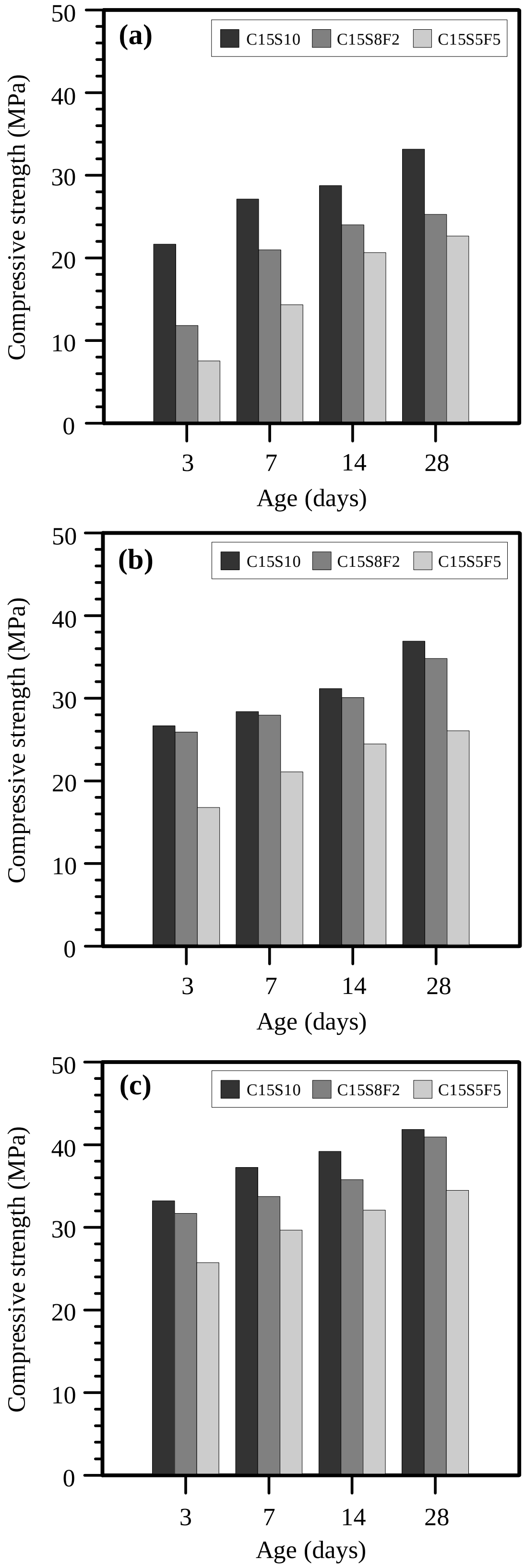

Fig. 2 Strengths development of hardened paste with different curing schemes: (a) T20, (b) T30 and (c) T40

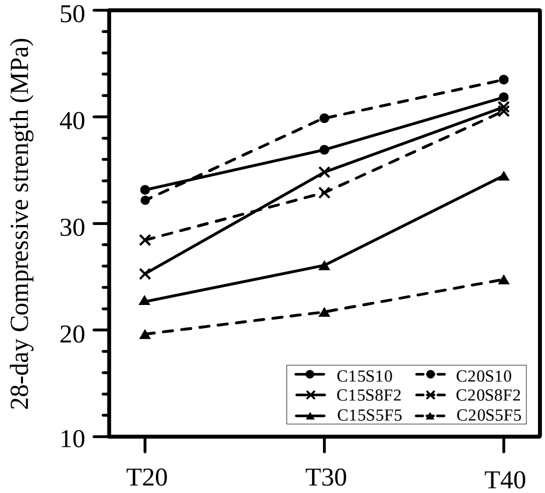

Fig. 3 The effect of additional CFBC fly ash in compressive strength

3.3 XRD analysis

The analysis of XRD results show the crystalline hydration products of SFC paste for different initial curing temperatures. Fig. 4 illustrates an example of XRD patterns using mix C15S8F2. It indicates that the hydration products were mostly found in the form of ettringite (AFt), aluminum-modified calcium silicate hydrate (C–A–S–H) gel, mullite, and quartz. It also can be seen that when the 2θ has a larger peak approximately at 30°, the peak position represents amorphous C–A–S–H gel. This gel is produced due to high content of calcium in the solution. The presence of high calcium in slag and CFBC fly ash leads to the formation of C–A–S–H type gel (Gao 2015). When the temperature is elevated and the 2θ is at 30°, the large peak is more obvious which means more amorphous gel was formed. The results also showed that 2θ had obvious peaks approximately at 26° and 32° which were confirmed to be mullite and quartz (Chen 2015). (Nguyen 2014) mentioned that when CFBC fly ash reacts with the water, $CaSO_4$ dissolves and releases Ca^{2+} and SO_4^{2-} ions. Thus the lime in CFBC fly ash reacts with the water and forms $Ca(OH)_2$ that useful in order to increase the pH of paste. (Nguyen 2015) pointed out that the formation of mullite and quartz due to the presence of class F fly ash as the precipitated hydration product of HVFA cement paste. (Park 2017) stated that CFBC fly ash contains sufficient amount of sulfate ions to enhance the formation of ettringite in the controlled-low strength material (CLSM) until 56 days. Consequently, the strength development was delayed as ettringite formed continuously until later ages.

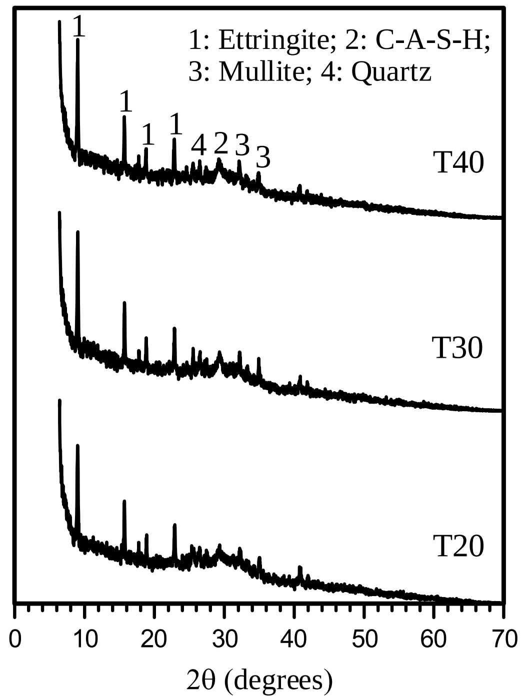

Fig. 4 XRD patterns of mix C15S8F2

4. CONCLUSIONS

This paper presented the results of experimental study on the engineering properties of hardened paste containing ground granulated blast furnace slag, class F fly ash and CFBC fly ash subjected to various initial elevated curing temperatures. The factors that influenced the strength of paste were investigated. The following conclusions can be summarized as follows:

(1) The presence of CFBC fly ash in the mixture generated the alkaline environment. The addition of CFBC fly ash above 5% showed the stable pH value approximately at 12.85. High pH value is an important factor in dissolving the slag.

(2) The compressive strengths both at early and later ages were improved after cured in the elevated temperatures due to the rapid reaction rate associated with the microstructural changes. The substantial strength increment was observed at 61.97% when class F fly ash was used as slag substitution in the amount of 20%. Moreover, the highest compressive strength was achieved at 41.84 MPa when there was no slag replacement and CFBC fly ash was fixed at 15%, however the induction of class F fly ash content by 20% had a comparable result that can be considered to improve the workability.

(3) The compressive strength development was also influenced by CFBC fly ash content. At high temperature, the CFBC fly ash was more active which resulted in better compressive strength. The result showed 20% CFBC fly ash was proposed to improve strength even for later ages.

(4) The major hydration products of hardened ternary paste were examined by X-ray diffraction (XRD). Ettringite, C–A–S–H gel, mullite, and quartz were found in the paste as a result of hydration process.

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