Semesta Teknika
Vol. 26, No. 2, 194 - 202, November 2023
DOI: https://doi.org/10.18196/st.v26i2.19732

Properties of Concrete Containing Type-C Fly Ash Under Elevated Temperature

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Keywords:
Type C fly ash; concrete; elevated temperature; residual strength

Abstract
High temperatures affect the properties of the concrete material. The changes generally depend on the quality of the concrete and the content of added ingredients during concrete mixing. This article examines the strength, weight, and visual changes of normal and high-strength concrete with the addition of class C fly ash (FA) under elevated temperature. FA was added as much as 15% by cement weight in each concrete type. The specimens consisted of four types concrete: normal concrete, normal concrete + FA, high-strength concrete, and high-strength concrete + FA. The fire test was carried out after 45 days curing time for 3 hours with variations in combustion temperature of 500ºC and 1000ºC. Visually, the concrete changes color to yellow-white with micro-cracks after being exposed to a temperature of 500ºC, while at 1000ºC, the surfaces of the concrete turns white, and there are larger and more apparent cracks. Furthermore, adding class C FA to high-strength concrete does affect the fire resistance level because it showed almost the same residual compressive strength after being exposed to both elevated temperature of 500°C and 1000°C.

INTRODUCTION

In the event of a fire, the temperature can increase drastically and affect the various elements present in the material. Concrete material has a reasonably sufficient ability to withstand the effects of high temperatures. In a fire situation, concrete tends to be more resilient than materials such as steel or wood. This is due to the nature of concrete with less thermal conductivity, which limits the depth of heat penetration. Likewise, the dimensions of the concrete are relatively large enough so that the possibility of high heat effects is generally only on the surface of the concrete.

Despite concrete having better fire resistance than other materials, the properties of the concrete material are still affected by high temperatures. Several studies stated a decreased quality and other properties after fire exposure (Memon et al., 2019; Yu et. al, 2019). Fire for three hours with a maximum temperature of 700ºC resulted in a reduction in rate of 43% (Kencanawati et al., 2015). Furthermore, a weight reduction of concrete occurs when the concrete reaches a higher temperature during firing. This happens because the concrete pores become more air-filled as they continue to hydrate. In addition, weight loss occurs if spalling is formed at higher firing temperatures. Cracks in concrete due to air pressure and higher combustion temperatures can also load sustaining ability of the concrete. This is due to the water capillary pressure on the cement paste in the concrete. Therefore, even small cracks in concrete due to water pressure can reduce the bearing capacity of concrete. The more significant the combustion temperature, the greater the decrease in the carrying capacity of the concrete in sustaining existing loads (Zhang, 2011).

In addition, the quality of concrete also affects the fire resistance properties of concrete material. Higher-strength concrete has worse fire resistance properties than lower-strength concrete (Phan, 1996). Concrete with compressive strength of 350 kg/m^2 shows lower residual strength than concrete with 250 kg/m^3 (Bayuasri et al., 2006). Higher-strength concrete has tighter pores so that water vapor is pushed out and compresses the surrounding cement paste (Khoury, 2008; Kencanawati, 2021).

High-strength concrete often uses mineral additives such as fly ash (FA). Fly ash is a result of coal combustion at PLTU. Using coal combustion waste ash from power plants is expected to reduce the abundant FA significantly. Based on its mineral content, FA is classified into Class F, Class C, and Class N. Type N fly ash is fly ash that can be produced from the combustion process or not from the combustion process, such as volcanic ash. This fly ash has pozzolanic properties. Type F fly ash contains less than10% CaO produced from burning coal of power plant. This type of fly ash also contains more than 70% of compounds (SiO_2 + Al_2O_3 + Fe_2O_3) and has pozzolanic properties. The type-C Fly ash contains CaO more than 10%, produced from burning coal. Besides CaO, it contains compounds (SiO_2 + Al_2O_3 + Fe_2O_3) more than 50% and has pozzolanic properties (Xu, & Shi, 2018). Class F fly ash concrete has been studied globally because this type has a higher pozzolan content (Klima, 2022; Saha, 2018; Siddique, 2004). Meanwhile, due to its lower pozzolanic content, type-C fly ash is not adequate in providing a pozzolanic effect on concrete (Yildirim et al., 2011). Therefore, this article discusses the effect on adding class C fly ash to normal and high-strength concrete at elevated temperatures to evaluate the correlation with the concrete fire resistance performance.

RESEARCH METHODS

Material

Fly ash was generated from coal incineration at Jeranjang Power Plant to supply electricity demand on Lombok Island, West Nusa Tenggara Province. Jeranjang Power Plant is a power plant that utilizes steam pressure energy generated from heating water using coal as fuel. Based on mineral content testing, the FA produced from Jeranjang power plant was classified as type C, where the total content of silica oxide, alumina oxide, and iron oxide was above 50% (Pathurahman et al., 2021). Details of mineral content are described in Table 1.

Table 1. Properties of FA

Chemical composition	Content (%)
SiO_2	15.80
Al_2O_3	3.80
Fe_2O_3	30.70
SO_3	4.10
CaO	41.20
SiO_2 + Al_2O_3 + Fe_2O_3	50.30

Type 1 Portland cement was used as a binder. FA was used as an addition for as much as 15% of the weight of cement in normal and high-strength concrete mixture. Fine aggregate was a type of slightly coarse sand having a maximum diameter size of 5 mm, while coarse aggregate in the form of crushed stone had a 20 mm maximum diameter size. The results of the aggregate quality test are given in Table 2.

Table 2. Properties of the aggregate

Properties	Aggregate type	
	Fine aggregate	**Coarse aggregate**
Spesific gravity (Saturated surface dry)	2.53	2.66
Water absorption (%)	1.04	0.69
Impurities content (%)	4.77	-
Soundness (%)		
a 100 cycles	-	7.51
b 500 cycles	-	24.9

Concrete Mixture Proportion

Normal-strength concrete was manufactured with a water-binder ratio of 0.45, while high-strength concrete uses a water-binder ratio of 0.27. Because the water-binder ratio was very low at high-strength concrete, the superplasticizer was added at the time of mixing as much as 0.6% of the weight of the cement. The proportions of the concrete mix are explained in Table 3.

Table 3. Concrete mixture proportion

Composition (kg)	Normal-strength concrete	High-strength concrete
Water	205.50	205.50
Cement	451.11	751.85
Coarse aggregate	843.30	843.30
Fine aggregate	869.64	566.61
Superplastisizers	-	4.511

Specimens and Testing

The test object was concrete cubes having the sizes of 90 mm x 90 mm x 90 mm. There were four variations of the specimens, namely normal-strength concrete (NSC), normal-strength concrete with FA (NSC+FA), high-strength concrete (HSC), and high-strength concrete with FA (HSC+FA).

The fire test experiments were conducted after the concrete exceeded 45 days old. The maximum combustion temperatures were 500°C and 1000°C. The heat growth curve followed the National Standard SNI 1741-2008, the standard for the Building Structural Components Fire Resistance Testing for Preventing Fire Hazards in Houses and Buildings (SNI, 2008). The standard temperature growth curve is shown in Figure 1. After the targeted temperature was exceeded, it was kept constant for 3 hours to allow heat penetration inside the concrete body entirely.

After combustion, the specimens were loaded to compression to determine the residual post-fire compressive strength. The compressive strength test was also conducted after concrete reached 28 days old to determine its the quality. The compressive strength test was applied by a compression testing machine (CTM), as shown in Figure 2.

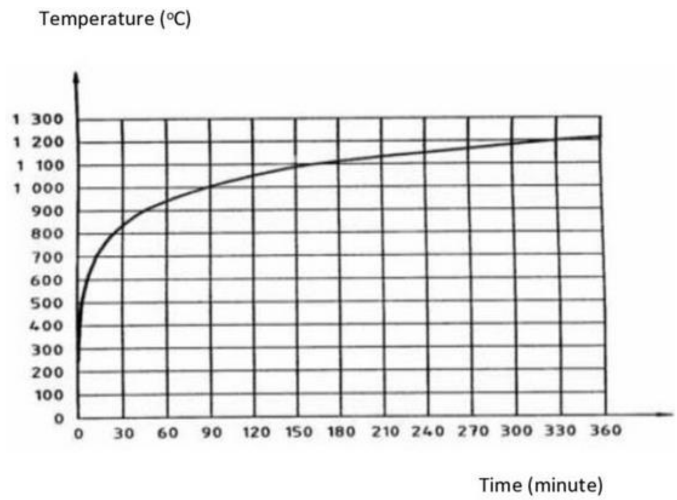

Figure 1. Heat standard curve (SNI 1741-2008)

Figure 2. Concrete compression testing

RESULTS AND DISCUSSION

Fresh Concrete Properties

Based on table 4, it can be stated that both normal-strength concrete and high-strength concrete have almost the same slump. The workability of the mixture can be maintained properly in the high-strength concrete mixture even though the water-cement ratio was very low. However, due to the role of superplasticizers, which can separate the particles in the mixture for producing adequate workability.

It can also be seen that by adding type-C FA to the concrete mixture generated in a decrease in the slump value. This occurs both in normal-strength concrete and high-strength concrete. FA consisted of very fine granules with a higher ability to absorb water resulting in lower slump values when compared to concrete mixtures without FA addition (Xu, & Shi, 2018). However, the slump reduction is not significantly found between concrete with FA and without FA.

Table 4. Concrete fresh properties

Specimens	Average slump (cm)
Normal-strength (NSC)	7.90
Normal-strength with fly ash (NSC+FA)	7.70
High-strength (HSC)	7.20
High strength with fly ash (HSC+FA)	7.05

28th Days Concrete Compressive Strength

Figure 3 shows the compressive strength of each type of concrete after 28 days curing time. The compressive strength of normal-strength concrete is 31.39 MPa, while the compressive strength of high-strength concrete is 69.82 MPa. With the addition of FA, the compressive strength increases to 38.65 MPa and 72.81 MPa for normal-strength concrete and high-strength concrete, respectively. The strength increase in NC was more significant with adding FA which is 23.12% on average compared to the increase of 4.28% in HSC. Adding FA to the concrete mixture as a mineral additive can produce more hydrated calcium silicate elements (Xu, & Shi, 2018). Type C FA used in this study contained pozzolanic oxide elements, which were more than 50% capable of bonding with calcium hydroxide elements, the by-products of the hydration of cement and water. In addition, because of its high calcium content, which is above 40%, FA itself can bind the pozzolanic oxide elements to produce hydrated calcium silicate elements as a binder to gain the strength of concrete immediately (Ashtiani, 2013).

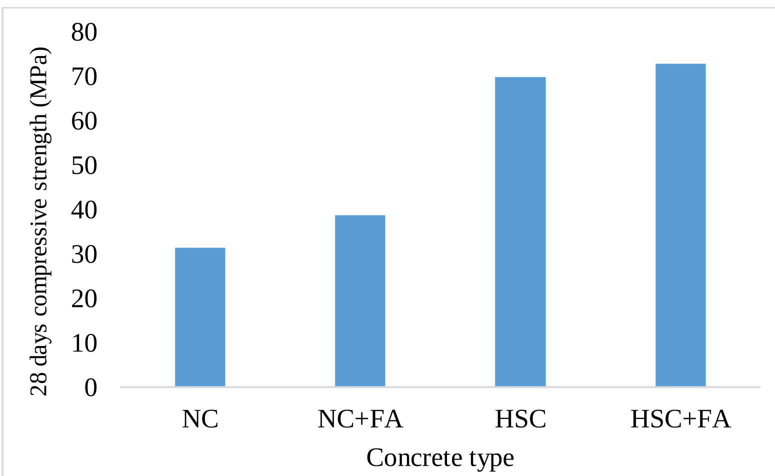

Figure 3. Concrete compressive strength

Visualization of Post-fire Concrete

Discoloration occurs in post-fire concrete. The color changes depending on the fire temperature experienced by the concrete. During temperature of 500°C, the color of the concrete changes to yellowish, which occurs due to the formation of iron salt compounds in coarse aggregate and fine aggregate; as a result, it causes the concrete to change color. It is in-line with research conducted by Srihayati, et al. (2021), which produced a yellowish concrete color at 500°C. When burning at 1000°C, the color of the concrete is found to turn white. This happens due to the carbonization process so that calcium carbonate ($CaCO_3$) is formed, which is whitish when the concrete experiences of a temperature of 800°C. Similar to the experiment conducted by Bayuasri et al. (2006), an experimented-on concrete with a temperature of 900°C found much white powder in the concrete surfaces. Furthermore, the same color change occurred in the concrete using FA and those without FA. Table 5 shows the visualization of the color change in post-combustible concrete.

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In addition to discoloration, cracks also occur on the post-fire concrete surface. At 500°C, microcracks begin to appear in the concrete containing FA and worsen at the temperature of 1000°C. FA makes concrete denser so that there tends to be pressure from water vapor in the deepest pores at high temperatures against the surrounding cement paste (Xu, & Shi, 2018).

Tabel 5. Visulization post-fire concrete

Concrete type	Temperature		
	Ambient	500°C	1000°C
NC			
NC+FA			
HSC			
HSC+FA			

Post-fire Concrete Weight

The greater the temperature experienced by the concrete, the weight of the concrete decreases. Figure 4 shows the weight loss of NC, NC+FA, HSC, and HSC+FA concrete at 500˚C by 10.7%, 12.9%, 8.1%, and 8.3% respectively, compared to the weight at ambient temperature. Whereas at a temperature of 1000˚C, the decrease occurred by 13.7%, 15.3%, 11.7%, and 13.2% when compared to the weight of the concrete before being fired. Furthermore, it is observed that the weight reduction in high-strength concrete is greater than in normal-strength concrete. Higher-strength concrete is usually denser, so the remaining hydration water has difficulty escaping during high temperatures and forces the surrounding cement, causing cracks and spalling. Thus, the weight of the concrete is reduced.

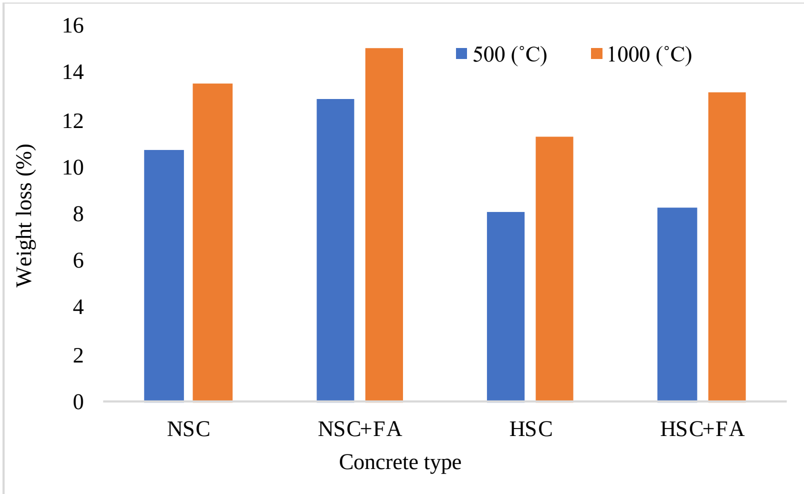

Figure 4. Concrete weight reduction after fire

Post-fire Concrete Compressive Strength

Table 6 illustrates the compressive strength of concrete after experiencing high temperatures at 500°C and 1000°C. The compressive strength at ambient temperature is also included as a comparison.

Table 6. Concrete compressive strength post-fire

Temperature (˚C)	**Concrete compressive strength (MPa)**			
	NSC	**NSC+FA**	**HSC**	**HSC+FA**
Ambient	31.39	38.65	69.82	72.81
500(˚C)	26.48	30.32	49.11	50.82
1000(˚C)	8.33	9.4	13.34	13.88

Concrete with fly ash has a higher compressive strength after the elevated temperatures than concrete without adding fly ash. This occurs both in normal-strength concrete and high-strength concrete. In ambient temperature, concrete with FA possesses a higher strength than concrete without adding FA is considered as the reason.

However, considering the post-fire residual compressive strength, the concrete with the addition of FA experiences a more dramatic decrease in compressive strength compared to the residual compressive strength of the concrete without FA. The remaining strength of normal-strength concrete and high-strength concrete are described in Figure 5. In addition, it can be considered that adding FA to high-strength concrete does affect the fire resistance level because it showed almost the same residual compressive strength resulting for both elevated temperature of 500°C and 1000°C. The remaining compressive strength of HSC and HSC+FA are 70.34% and 69.80% at 500°C and 19.11% and 19.06% at 1000°C, respectively.

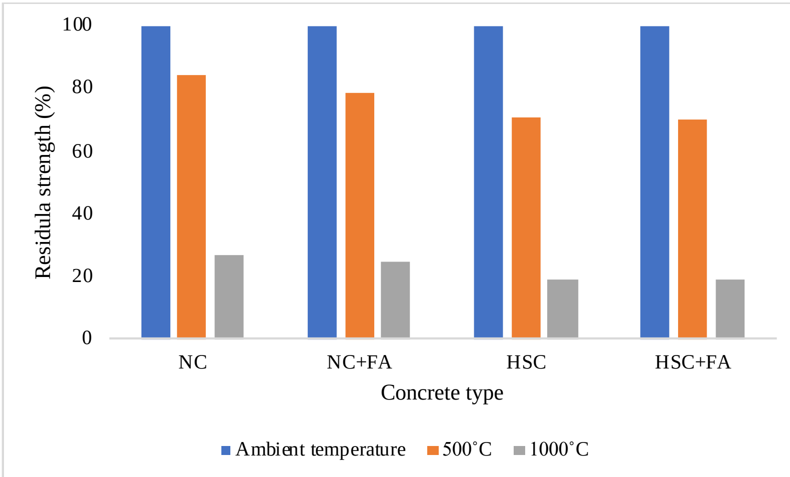

Figure 5. Concrete residual strength post-fire

CONCLUSION

This article discusses the influence of adding type-C fly ash (FA) on the properties of concrete exposed to high temperatures. FA is an additive in a mixture of normal and high-strength concrete. At normal temperature, the compressive strength of normal-quality concrete is 31.39 MPa, while the compressive strength of high-quality concrete is 69.82 MPa. With the addition of type-C FA, there is a rise in compressive strength of 38.65 MPa and 72.81 MPa for normal-strength concrete and high-strength concrete, respectively. After burning, there is no any differences discoloration found between the concrete using FA and those using FA. When the temperature extends to 500°C, the color of the concrete turns yellowish, whereas the whitish color is found in the concrete surfaces after being exposed to 1000°C.

Furthermore, there were a few differences in weight loss between concrete with and without FA addition after exposure to high temperatures. Concrete with FA has a higher compressive strength at elevated temperatures than concrete without adding fly ash. However, regarding the residual strength, the concrete with the addition of FA shows a more significant decrease in compressive strength than the those of normal-strength concrete. In addition, adding FA to high-strength concrete does affect the fire resistance level because it showed almost the same residual compressive strength resulting for both elevated temperature of 500°C and 1000°C.

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