Mechanical Properties of Lightweight Concrete Using Class F Fly Ash as a Partial Replacement for Ordinary Portland Cement

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Mechanical Properties of Lightweight Concrete Using Class F Fly Ash as a Partial Replacement for Ordinary Portland Cement

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Abstract. This study shows the mechanical properties of lightweight concrete (LWC) made by partially replacing ordinary Portland cement (OPC) with class F fly ash (FFA). Natural sand and pumice were used as the fine aggregate and coarse aggregate, respectively. Five LWC mixtures, M1, M2, M3, M4, and M5, were made by replacing, by weight, of 0%, 10%, 20%, 30 %, and 40% OPC with FFA, respectively. The mix proportion of LWC, by weight, was 1.00 binder: 3.24 fine aggregate: 1.19 coarse aggregate, and the water-binder ratio was 0.32. Tests of the LWC mechanical properties were conducted at the hydration time of 28 and 56 days using 150 by 300 mm cylindrical specimens. The results indicate that the use of FFA as a partial replacement for OPC improved the development of the mechanical properties of LWC. The compressive strength and the modulus of elasticity of the LWC increased in all the mixtures during the hydration time. The optimal proportion of FFA for replacing OPC in LWC is about 20%. With this optimal proportion and after 56 days of hydration, the compressive strength and the modulus of elasticity are, respectively, about 113% and 105% of those produced by LWC made with 100% OPC.
Keyword: Lightweight Concrete, Fly Ash, Compressive Strength

1. Introduction

Fly ash is a heterogeneous by-product produced from the burning of pulverised coal in power generation plants. It is the unburned residue carried away from the burning zone in the boiler by the flue gases and then collected by either mechanical or electrostatic separators. It is composed of fine spherical glassy particles. The use of fly ash in cement and concrete technology started a long time ago and is becoming more and more popular nowadays due to the many benefits offered by this residue, related to its pozzolanic and/or cementitious properties [1-3]. It can be used as a raw material to produce blended Portland cement or added as an admixture during the mixing of the concrete. Using this by-product in this field offers many benefits and provides a good strategy for increasing its economic value and reducing the CO_2 emissions from the production of Portland cement.

Based on the relative quantity of the three major chemical constituents, ASTM C-618 [4] classifies fly ash into two categories: class C and class F. Fly ash containing 50-70% of silica, aluminium, and iron oxides (SiO_2+Al_2O_3+ Fe_2O_3) is classified as class C. If the sum of these three oxides is more than 70% then it is classified as class F. Fly ash produced from the burning of lignite or sub-bituminous coals, usually classified as class C fly ash, possesses simultaneously pozzolanic and cementitious properties due to its CaO content, while that from the burning of anthracite or bituminous coals, classified as class F fly ash, possesses pozzolanic properties [1-3].

Many studies and fields applications have demonstrated that both fresh and hardened concrete can be significantly improved by incorporating fly ash in the manufacture of Portland cement or concrete [5-13]. However, the quantity of fly ash that can be used to maximise the performance of these construction materials varies from case to case. This is related to the fact that the physical, mineralogical, and chemical properties of fly ash vary widely, depending on the nature and origin of the coals as well as the burning conditions within a power generation plant [11, 14-16]. Therefore, for any given fly ash, there will be an optimum quantity of fly ash that can be actually used for maximising its benefits. In this study, the mechanical properties of lightweight concrete (LWC) using class F fly ash (FFA) as a partial replacement for ordinary Portland cement (OPC) were observed. The objective of this study is to evaluate, with hydration time, the development of the LWC's compressive strength and modulus of elasticity using different quantities of FFA in order to find out the optimal use of FFA for replacing OPC.

2. Materials and Experimental Method

2.1. Materials

Type 1 Portland cement, OPC, in accordance with SNI 15-2049-2004 [17], was obtained from a Portland cement producer in Indonesia. Fly ash was obtained from a power generation plant in South Sumatera. Table 1 shows the chemical composition of the OPC and FFA. Here, it can be noted that the sum of the silica, aluminium, and iron oxides is 74.4% which is more than 70%, so, according to ASTM-C618, this ash can be classified as Class F Fly Ash (FFA). However, it should also be noted that the CaO content in this ash is almost 10%.

Table 1. Chemical composition of the OPC and FFA.

Oxides	OPC	FFA
Al_2O_3 (%)	4.3	5.6
CaO (%)	59.9	9.6
SiO_2 (%)	26.2	61.9
Fe_2O_3 (%)	3.8	6.9

Local tap water as well as a modified polycarboxylate copolymers superplasticizer (SP) were used for all the mixtures. Natural sand (NS) and pumice (PM) were used as the fine aggregate and coarse aggregate, respectively. The nominal maximum grain size of NS and PM is 4.8 mm and 12.5 mm, whereas their fineness modulus is 3.22 and 6.38, respectively. Table 2 shows the physical properties of the NS and PM concerning their unit weight, specific gravity, and absorption.

Table 2. Physical properties of the NS and PM.

Physical Properties	Natural Sand	Pumice
Unit weight (g/cm^3)	1.6	0.5
Specific gravity SSD	2.3	1.1
Absorption (%)	5.5	31.1

2.2. Experimental Method

2.2.1. Mixture Proportions

For this study, five LWC mixtures were made, namely: M1, M2, M3, M4, and M5. The mixture proportion, by weight, was 1.00 binder: 3.24 fine aggregate: 1.19 coarse aggregate with a water to binder ratio of 0.32. In each mixture, 0.4% SP by binder weight was added. The binder was a blend of OPC and FFA. The five LWC mixtures were made by replacing OPC with 0%, 10%, 20%, 30%, and 40% of FFA, by weight, respectively. The proportions in the LWC mixtures are presented in table 3.

Table 3. LWC mixture proportions.

Material	Mixture				
(kg/m3)	M1	M2	M3	M4	M5
OPC	326	293.4	260.8	228.2	195.6
FFA	0	32.6	65.2	97.8	130.4
NS	1057	1057	1057	1057	1057
PM	389	389	389	389	389
Water	105	105	105	105	105
SP	1.3	1.3	1.3	1.3	1.3

2.2.2. Preparation and Specimen Casting

The LWC mixing process for all the mixtures was done using the same procedure. First, SP was added into the mixing water. Next, the OPC, NS, and PM were mixed for two minutes in a concrete mixer, and then 75% of the water was added and mixed for three minutes. Finally, the remaining water was added, and the mixture was mixed for an additional two minutes until it became homogenous. After mixing, each mixture was used to cast cylindrical specimens which had a diameter of 150 mm and a height of 300 mm. These specimens were kept in the molds for one day and were then remolded and cured with wet burlap until they were used for the compressive strength and modulus of elasticity tests. The preparation of the cube specimens, according to Indonesian Standard SNI 2493:2011 [18], is illustrated in figure 1.

Figure 1. Preparation of the Specimens.

2.2.3. Compressive strength and modulus of elasticity tests

Tests for the LWC properties concerning compressive strength and modulus of elasticity were carried out at the age of 28 and 56 days. Three cylinder specimens were used for each test. The compressive strength and the modulus of elasticity tests were carried out according to SNI 03-1974 [19] and ASTM C-469-94 [20], respectively. Figure 2 shows a mechanical properties test being carried out.

Figure 2. Mechanical properties test.

3. Result and Conclution

3.1. Results

3.1.1. Compressive Strength

The compressive strength test results for the different LWC mixtures at 28 and 56 days are presented in figure 3. It can be clearly observed that the compressive strength of the LWC in all the mixtures increases with the hydration time.

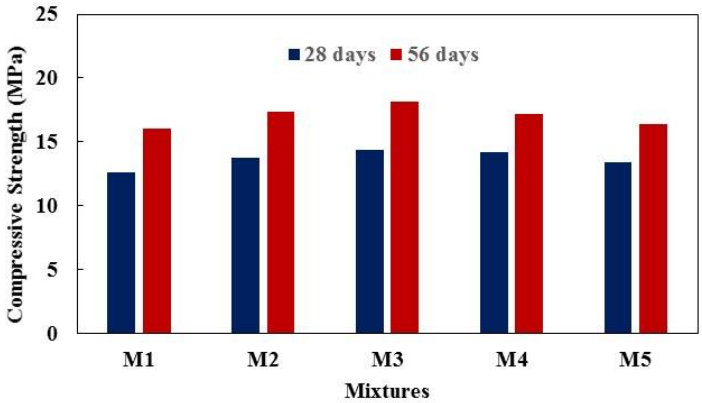

Figure 3. Compressive strengths of the mixtures at two different times**.**

At 28 days, control mixture M1, made with 100% OPC, develops a compressive strength of about 12.6 MPa, while mixtures M2, M3, M4, and M5 achieve compressive strengths of about 13.8, 14.3, 14.2, and 13.4 MPa, respectively. The compressive strengths of M1, M2, M3, M4, and M5 reach about 16.0, 17.4, 18.1, 17.2, and 16.4 MPa, respectively, after 56 days. During this hydration period, the compressive strength gains of M1, M2, M3, M4, and M5 are about 27%, 26%, 26%, 21%, and 22%, respectively.

It is also observed that the compressive strength increases up until the 20% replacement of OPC with FFA, and subsequently it tends to decrease. However, it should be noted that LWC made with 40% replacement of OPC still produces a slightly higher compressive strength than LWC made with 100% OPC. After 56 days, the compressive strengths of M2, M3, M4 and M5 are about 108%, 113%, 107%, and 102%, respectively, compared with that of M1.

3.1.2. Modulus of Elasticity

The modulus of elasticity test results of the various LWC mixtures at 28 and 56 days are illustrated in figure 4. As has been observed in the case of compressive strength, here, it can be seen that the modulus of elasticity of LWC in all the mixtures also increases with the hydration time.

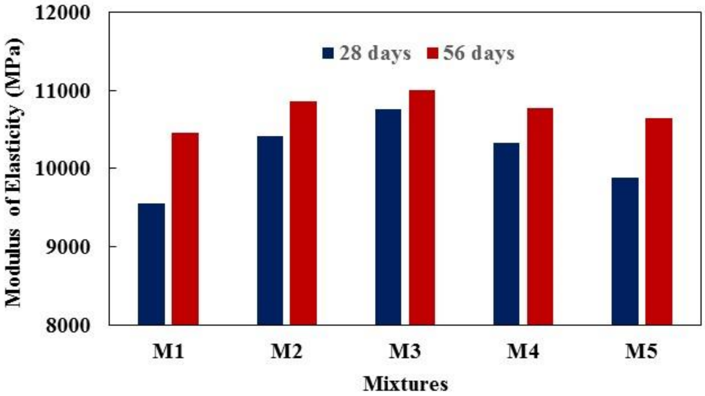

Figure 4. Modulus of elasticity of the mixtures at two different times.

After 28 days, control mixture M1, made with 100% OPC, produces a modulus of elasticity of about 9549 MPa, while mixtures M2, M3, M4, and M5 develop a modulus of elasticity of about 10409, 10767, 10333, and 9887 MPa, respectively. The modulus of elasticity of M1, M2, M3, M4, and M5 are about 10460, 10866, 11007, 10775, and 10651 MPa, respectively, after 56 days. In this hydration period, the modulus of elasticity gains of M1, M2, M3, M4, and M5 are about 10%, 4%, 2%, 4%, and 8%, respectively.

It should also be noted that the modulus of elasticity increases up until the 20% replacement of OPC with FFA, and subsequently it tends to decrease. However, it should be clearly noted that LWC made with 40% replacement of OPC still produces a slightly higher modulus of elasticity than LWC made with 100% OPC. After 56 days, the modulus of elasticity of M2, M3, M4 and M5 are about 104%, 105%, 103%, and 102%, respectively, compared with that of M1.

3.2. Discussion

The results from the compressive strength and modulus of elasticity tests for specimens with 100% OPC or replaced with 10%-40% FFA showed progressive improvement with the hydration time. During the hydration time, from 28 to 56 days, it is evident that the compressive strength and the modulus of elasticity increase in all the mixtures. This phenomenon is in agreement with that observed by Siddique [9], Crouch et al. [11], and Salain et al. [13]. The progressive improvement of these hardened properties could be related to the development of the cementitious hydration products in the LWC mixtures due to binder hydration. It is generally known that the quantity of cementitious hydration products in concrete, with sufficient curing, increases with the hydration time. This increase makes the bond between the binder and aggregate stronger and the porosity of concrete reduces due to a reduction in large pores of concrete system. This condition provides an improvement in the strength and modulus of elasticity of the system [1-3].

It should also be noted that the compressive strength and the modulus of elasticity gains produced in the mixtures M2, M3, M4, and M5 are relatively comparable than those produced in control mixture M1. Furthermore, it is interesting to note that the development of the compressive strength and the modulus of elasticity in the mixtures M2, M3, M4, and M5 are relatively faster than that of the control mixture M1. This is strongly related to the cementitious and pozzolanic reactions of FFA contributing to the improvement of their mechanical properties during the hydration time.

Moreover, it is also observed that the compressive strength and the modulus of elasticity of LWC increase with the replacement of OPC with FFA up until the 20% replacement, and subsequently they tend to decrease. Accordingly, the optimum replacement of OPC with FFA is 20%. However, the mechanical properties of the LWC are still acceptable with a replacement of OPC of up to 40% FFA. Hence, the use of FFA in this study for replacing OPC is limited to 40% in order to produce LWC that has mechanical properties which are comparable to, or better than, LWC made with 100% OPC. This limitation strongly depends on the availability of the free lime $Ca(OH)_2$ obtained from OPC hydration, as well as the calcium, silica, and alumina reactive available in FFA for cementitious and pozzolanic reactions. In fact, calcium contributes to the cementitious reaction, while both reactive silica and alumina contribute to the pozzolanic reaction [1-3].

Generally, the lime (CaO) content in FFA is low, ranging between 2 and 5% [3], whereas in this case, the CaO content is 9.6%. Therefore, it is possible that the higher CaO content in this FFA also contributes to the higher quantity of FFA that can be used to replace OPC to keep the cement hydration process. Accordingly, for certain situations, the type as well as the physical and chemical properties of fly ash will always determine the amount of fly ash that can be used to replace OPC in making blended Portland cement.

4. Conclusions
Based on the results of this study, the following conclusions are drawn:
- The class F fly ash used in this study demonstrates significant pozzolanic and hydraulic properties.
- This fly ash can be used to replace up to 40% of OPC in order to produce LWC that has mechanical properties which are comparable to LWC made with 100% OPC.
- The optimum proportion of this fly ash for replacing OPC in LWC is about 20%.
- With this optimum proportion and after 56 days of hydration, the compressive strength and the modulus of elasticity produced are about 18 MPa and 11,000 MPa which are, respectively, about 113% and 105% of those produced by LWC made with 100% OPC.

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