Experimental study on the properties of high-performance concrete made with class C fly ash

I Made Alit Karyawan Salain[1,*], *I Nyoman* Sutarja[1], and *Teguh* Arifmawan Sudhiarta[1]

[1]Department of Civil Engineering, Universitas Udayana, Denpasar, Indonesia

Abstract. This experimental study presents the properties of high-performance concrete (HPC) made by partially replacing type I Portland cement (OPC) with class C fly ash (CFA). The purpose of this study is to examine, with hydration time, the development of the compressive strength, the splitting tensile strength and the permeability of HPC utilizing different quantity of CFA. Four HPC mixtures, C1, C2, C3, and C4, were made by utilizing respectively 10%, 20%, 30% and 40% of CFA as replacement of OPC, by weight. One control mixture, C0, was made with 0% CFA. The mix proportion of HPC was 1.00 binder: 1.67 fine aggregate: 2.15 coarse aggregate with water to binder ratio 0.32. In each mixture, it was added 5% silica fume and 0.6% superplasticizer of the weight of the binder. Tests of HPC properties were realized at the age of 1, 3, 7, 28, and 90 days. The results indicate that CFA used to partially replace OPC in HPC shows adequate cementitious and pozzolanic properties. The compressive strength and the splitting tensile strength of HPC increase while the permeability coefficient decreases with increasing hydration time. It is found that the optimum replacement of OPC with CFA is 10%, however the replacement up to 20% is still acceptable to produce HPC having practically similar harden properties with control mixture. At this optimum replacement and after 90 days of hydration, the compressive strength, the splitting tensile strength and the permeability coefficient can reach 68.9 MPa, 8.3 MPa and 4.6 E-11 cm/sec respectively. These results are 109%, 101%, and 48% respectively of those of control mixture.

1 Introduction

Concrete is presently the most popular used construction material in the world. Many studies have been realized to improve the properties of concrete including cost, strength, durability, or ease of application. High-performance concrete (HPC) represents one of the advances in concrete technology. HPC, according to the American Concrete Institute (ACI), "is concrete meeting special combination of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing and curing practices" [1]. The properties of HPC are specially developed for the requirement of specific constructions and environments. Some of HPC

* Corresponding author: imaksalain@unud.ac.id

properties needed can be a high compressive strength, high early strength, high modulus of elasticity, high abrasion resistance, high durability, low permeability, etc.

Although HPC is generally composed of relatively the same materials as usual concrete, however, it does require the use of materials with specific properties and their proportions have to be carefully determined to meet the performance needed for the constructions and environments [2]. Therefore, HPC must be made with selected high-quality materials and optimized mixture designs. Typically, this type of concrete will have a low water-binder ratio to ensure the achievement of high strength gain. Consequently, superplasticizer must be used to make this type of concrete fluid and workable. The maximum size of coarse aggregate in HPC is generally smaller than that in normal concrete. Furthermore, mineral admixtures, especially pozzolanic materials, are usually incorporated in HPC mixtures to reduce the cement content and improve its properties simultaneously.

Many studies have been realized previously to examine the performance of HPC utilizing mineral admixtures. Naik et al. [3] evaluated the properties of HPC incorporating high-lime fly ash. The results of this evaluation showed that HPC incorporating fly ash at 30% cement replacement could be proportioned for high-strength applications. In general, concrete mixtures up to 50% cement replacement with fly ash showed satisfactory performance and appropriate for structural applications. Li et al. [4] examined the influence of the addition of fly ash, microsilica, and calcium nitrate on chloride diffusion of HPC. The results of this examination showed that the 25% addition of fly ash by weight of cement improved the mix's resistance to chloride diffusion. The improvement was especially evident when 25% of fly ash and 10% of microsilica by weight of cement were added into the mixture together. The addition of calcium nitrate into the mix, however, resulted in deterioration in an improvement of resistance to chloride diffusion enhanced by the incorporation of fly ash and microsilica. Hassan et al. [5] studied the influence of silica fume and fly ash on the properties of superplasticised HPC. The results showed that mineral admixtures improved the properties of HPC, but at different rates depending on the binder type. Silica fume contributed to both short- and long-term properties of concrete, however, fly ash needed a relatively long time to get its beneficial effect. A study conducted by Zhang et al. [6] showed that mineral admixtures significantly reduced the hydration heat and the exothermic rate and prolonged the arrival time of the highest temperature. Isaia et al. [7] studied the effect of the replacement of 12.5%, 25%, and 50% cement by fly ash, rice husk ash, and limestone filler. The results of this study showed that the pozzolanic and physical effects have increased as the mineral addition increased in the mixture. These effects were higher after 91 days than after 28 days. Lee et al. [8] investigated the effect of fly ash on the autogenous shrinkage of HPC. The results of this investigation showed that autogenous shrinkage of HPC containing fly ash decreased compared with that without fly ash - the higher the fly ash replacement percentage, the lower the level of autogenous shrinkage. However, although partial replacement of cement by fly ash could effectively reduce autogenous shrinkage of HPC, incorporating fly ash only might not prevent early-age cracking. The results of a study realized by Chang [9] proved that the utilization of fly ash and slag were beneficial to the rheology of HPC in enhancing its strength development and durability. Vejmelková et al. [10] investigated the influence of fly ash on the properties of HPC. The results of this investigation showed that 10% of fly ash as Portland cement replacement could be considered as a suitable amount from the point of view or preserving the high-performance properties of the concrete.

Those studies indicate that the utilization of mineral admixtures in HPC improves its properties. However, it is noted that the improvement observed varies significantly with the types and the replacement levels of mineral admixtures used. This can be related to the inherent variability of mineral admixtures due to the different sources and processing methods [11-14]. Therefore, there is always a need for studying the optimized mixture of HPC according to performance targeted and the type of mineral admixtures used.

In this study, the hardened properties of HPC utilizing class C fly ash as a partial replacement of ordinary Portland cement were tested. This study aims to examine the development of the compressive strength, the splitting tensile strength and the permeability of HPC made with a different quantity of fly ash.

2 Materials and experimental methods

2.1 Materials

The cement used was type I Portland cement (OPC), which complies with the requirements of SNI 15-2049 [15]. Fly ash (CFA) used, obtained from one of electric power generating plant in Indonesia, was classified as class C fly ash according to ASTM C 618 [16]. The silica fume (SF) used as a dry powder. Table 1 presents the chemical composition of OPC, CFA, and SF.

Table 1. Chemical composition of OPC, CFA and SF.

Component	OPC	CFA	SF
Al_2O_3 (%)	4.98	5.96	2.85
CaO (%)	60.12	12.96	0.23
SiO_2 (%)	22.14	62.68	93.12
Fe_2O_3 (%)	2.84	7.91	1.21
SO_3	1.89	2.15	0.42

Natural sand (NS) and crushed stone (CS), confirmed to SNI 03-2834 [17], were respectively used as fine aggregate and coarse aggregate having a nominal maximum size of 4.8 mm and 12.5 mm. The grain gradation of NS and CS were kept constant having a fineness modulus of 2.79 and 6.45 respectively. Table 2 presents the physical properties of these aggregates. Local tap water and a commercially available aqueous solution of modified polycarboxylate copolymers superplasticizer (SP) were used for all mixtures.

Table 2. Physical properties of fine aggregate and coarse aggregate.

Material	Unit weight (g/cm^3)	Specific gravity	Abrasion (%)	Absorption(%)
NS	1.7	2.4	-	1.2
CS	1.4	2.5	26	2.1

2.2 Experimental methods

2.2.1 Mixtures proportion and specimens casting

Five mixtures were prepared in this study. One control mixture, C0, made with 100% OPC as a binder, was designed according to ACI 211.4R-93 [18] to have the 28-day compressive strength of 60 MPa. The designed mix proportion was 1.00 binder: 1.67 fine aggregate: 2.15 coarse aggregate with water to binder ratio 0.32. The other four mixtures, C1, C2, C3, and C4, were made by replacing OPC with 10%, 20%, 30%, and 40% of CFA, by weight, respectively. In each mixture, it was added 5% silica fume and 0.6% SP of the weight of the binder. The five mixtures proportion of HPC is presented in Table 3.

Table 3. Mixtures proportion of HPC (kg/m^3).

Material	**Mixtures**				
	C0	**C1**	**C2**	**C3**	**C4**
OPC	440	396	352	308	264
CFA	0	44	88	132	176
NS	736	736	736	736	736
CS	945	945	945	945	945
water	139	139	139	139	139
SF	22	22	22	22	22
SP	2.6	2.6	2.6	2.6	2.6

OPC = Ordinary Portland Cement, CFA = Coal Fly Ash, NS = Natural Sand,
CS = Crushed Stone, SF = Silica Fume, SP = Superplasticizer

The specimens were prepared following Indonesian Standard SNI 2493 [19]. For each mixture, concrete cylinders (150x300mm) were cast and compacted using a vibrating table. Twenty four hours after casting, they were demolded and then cured in water until strength and permeability test.

2.2.2 Strength and permeability test

Concrete properties analysis concerning compressive strength, splitting tensile strength and permeability were realized at the age of 1 day, 3 days, 7 days, 28 days, and 90 days. Three-cylinder specimens were used for each test. The compressive strength and the splitting tensile strength tests were realized according to SNI 03-1974 [20] and SNI 03-2491[21], respectively. The water permeability test was achieved by utilizing permeability concrete apparatus with three individual cells.

3 Results and discussion

3.1 Results

3.1.1 Compressive strength

The compressive strength test results of the different HPC mixtures up to 90 days are illustrated in Fig. 1. The results present the increase of compressive strength with hydration time for all mixtures.

At 1st day, control mixture C0 achieves compressive strength of 25.2 MPa, while mixtures C1, C2, C3, and C4 achieve compressive strength of 31.2, 28.6, 21.0, and 12.7 MPa respectively. The compressive strength of C0, C1, C2, C3, and C4 become 60.2, 60.3, 55.2, 54.0, and 49.0 MPa respectively after 28 days, and become 63.4, 68.9, 60.0, 58.5, and 52.5 MPa respectively after 90 days. From 28 days to 90 days, the compressive strength gains of C0, C1, C2, C3, and C4 are about 5%, 14%, 9%, 8%, and 7%, respectively. Therefore, it is noted that the compressive strength gain is more for HPC made with CFA than control mixture C0.

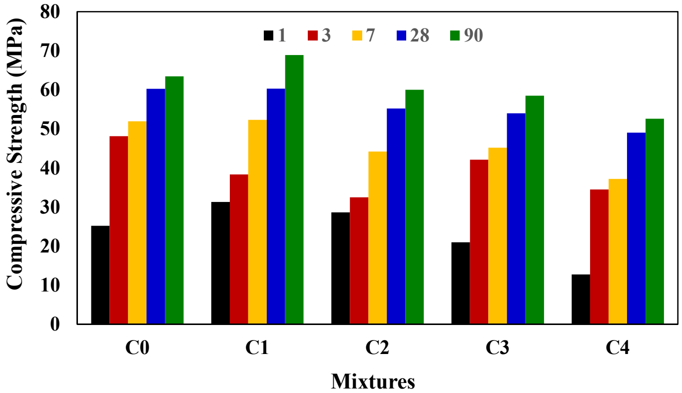

Fig. 1. Compressive strength versus mixtures.

In general, it is also observed that the compressive strength of HPC made with CFA increases with the replacement of OPC with CFA, until 10% replacement, and tends to decrease subsequently. However, it should be noted that the compressive strength produced is still acceptable until the replacement of OPC up to 20% CFA, especially after 90 days of hydration. In comparison with C0, the compressive strength of C1, C2, C3, and C4 are about 100%, 92%, 90%, and 81% respectively after 28 days and are about 109%, 95%, 92%, and 83% respectively after 90 days.

3.1.2 Splitting tensile strength

The splitting tensile strength test results of the different HPC mixtures up to 90 days are shown in Fig. 2. Like compressive strength results, splitting tensile strength in all mixtures also increases with the hydration time.

At 1st day, control mixture C0 achieves splitting tensile strength of 2.3 MPa, while mixtures C1, C2, C3, and C4 achieve splitting tensile strength of 4.4, 2.6, 1.8, and 1.6 MPa respectively. The splitting tensile strength of C0, C1, C2, C3, and C4 become 7.8, 7.8, 7.0, 5.6 and 4.4 MPa respectively after 28 days, and become 8.2, 8.3, 7.6, 6.3, and 5.1 MPa respectively after 90 days. From 28 days to 90 days, the splitting tensile strength gain of C0, C1, C2, C3, and C4 are about 4%, 6%, 8%, 12%, and 14%, respectively. Hence, it is also noted that the splitting tensile strength gain is more for HPC made with CFA than control mixture C0.

In general, it is also observed that the splitting tensile strength of HPC made with CFA increases with the replacement of OPC with CFA, until 10% replacement, and tends to decrease subsequently. However, it seems that the splitting tensile strength produced by replacing OPC up to 20% CFA is still adequate, especially after 90 days of hydration. The splitting tensile strength of C1, C2, C3, and C4 are about 99%, 89%, 72%, and 57% compared with that of C0 after 28 days and are nearly 101%, 92%, 77%, and 62% respectively after 90 days.

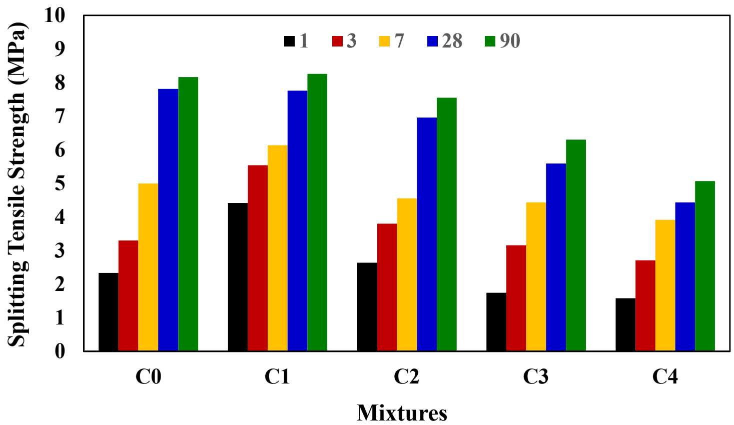

Fig. 2. Splitting tensile strength versus mixtures.

3.1.3 Permeability

The permeability test results of the different HPC mixtures up to 90 days are presented in Figure 3. The results show the decrease of permeability coefficient with the hydration time in all mixes.

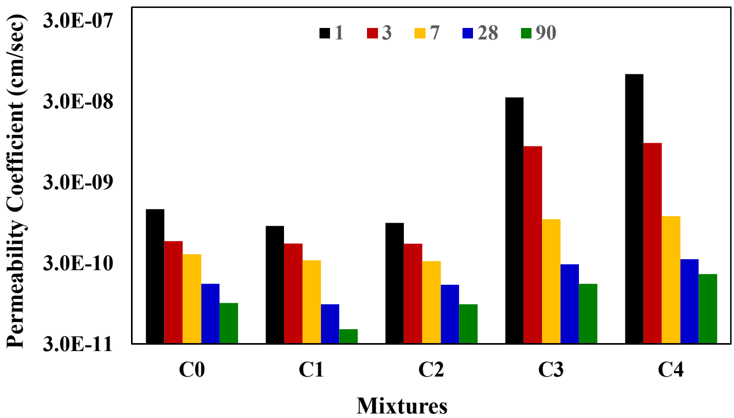

Fig. 3. Permeability coefficient versus mixtures.

At 1st day, the permeability coefficient of control mixture C0 is 1.4 E-09 cm/sec, whereas that of mixtures C1, C2, C3, and C4 are 8.7 E-10, 9.4 E-10, 3.4 E-08, and 6.5 E-08 cm/sec respectively. The permeability coefficient of C0, C1, C2, C3, and C4 become 1.7 E-10, 9.3 E-11, 1.6 E-10, 2.9 E-10, and 3.4 E-10 cm/sec respectively after 28 days, and become 9.6 E-11, 4.6 E-11, 9.3 E-11, 1.7 E-10, and 2.2 E-10 cm/sec respectively after 90 days. From 28 days to 90 days, the permeability coefficient of C0, C1, C2, C3, and C4 decrease about 42%, 51%, 43%, 42%, and 35%, respectively. In general, it is observed that the decrease of permeability coefficient is more for HPC made with CFA than control mixture C0, except for HPC made with 40% CFA.

Furthermore, it is noted that the permeability coefficient of HPC made with CFA decreases with the replacement of OPC with CFA, until 10% replacement, and tends to increase subsequently. However, it should be noted that the permeability coefficient produced is still acceptable until the replacement of OPC up to 20% CFA, especially after 90 days of hydration. The permeability coefficient of C1, C2, C3, and C4 are about 56%, 97%, 174%, and 203% respectively compared with that of C0 after 28 days, and are about 48%, 96%, 173%, and 229% respectively after 90 days.

3.2 Discussion

The test results of compressive strength, splitting tensile strength and permeability of HPC made either by utilizing 100% OPC or by replacing 10-40% OPC with CFA present progressive improvement with the hydration time. During the hydration time, from 1 day to 90 days, it is observed that the compressive strength and the splitting tensile strength increase and the permeability coefficient decreases in all mixtures. This phenomenon has also been found in other studies [13, 22]. The progressive improvement of these hardened properties is strongly related to the development of the cementitious hydration products in HPC mixtures due to binder hydration. It is well known that the quantity of cementitious hydration products in concrete, under adequate curing, increases with the increase of hydration time. The rise in this hydration product makes the bond between binder and aggregate getting stronger, and the porosity of concrete reduces due to a reduction in large pores of the concrete system. This phenomenon contributes to the improvement of the strength and impermeability of the system [23, 24]. Furthermore, it is also noted that the increase in strength and decrease in permeability are generally higher for HPC made with CFA than control mixture C0. This is due to cementitious and pozzolanic properties of CFA contributing to the improvement of their properties at early ages and long-term hydration respectively.

Furthermore, it is interesting to note that the development of the compressive strength, the splitting tensile strength and the permeability of C1 and C2 are relatively faster than that of control mixture C0 at early ages. This is actively contributed by cementitious reaction of CFA at the early hydration improving the hardened properties of those HPC. However, this effect is not observed in C3 and C4. It seems that this could be related to the fact that the quantity of OPC available for reactions in this mixtures is much lower than that of C1 and C2.

Moreover, it is also observed that the compressive strength and the splitting tensile strength of HPC increase with the replacement of OPC with CFA, until 10% replacement, and tend to decrease subsequently. On the contrary, permeability decreases with the replacement of OPC with CFA, until 10% replacement, and tends to increase consequently. Accordingly, the optimum replacement of OPC with CFA is 10%. However, the hardened properties of HPC produced are still acceptable until the replacement of OPC up to 20% CFA. Hence, the use of CFA in this study as replacement of OPC is limited to 20% to produce HPC having hardened properties comparable to or better than HPC made with 100% OPC. This limitation strongly depends on the availability of free lime $Ca(OH)_2$ obtained from OPC hydration as well as calcium, alumina, and silica reactive available on CFA for cementitious and pozzolanic reactions. Calcium will contribute to cementitious reaction while alumina and silica reactive will contribute to a pozzolanic reaction. Therefore, if other factors are set constant, the types and the properties of fly ash will always control the quantity of fly ash that can be used as partial replacement of OPC.

4 Conclusions

The following conclusions are drawn from the results of this experimental study. Class C fly ash used as a partial replacement of OPC in this work demonstrates adequate cementitious and pozzolanic properties. The compressive strength, the splitting tensile strength and the permeability of HPC made by replacing OPC with 10%, 20%, 30%, and 40% of CFA progressively improve with the hydration time. The optimum replacement of

OPC with CFA is 10%. However, the replacement up to 20% is still acceptable to produce HPC having practically similar harden properties with HPC made without CFA. At this optimum replacement, the compressive strength, the splitting tensile strength, and the permeability coefficient can reach 68.9 MPa, 8.3 MPa and 4.6 E-11 cm/sec respectively after 90 days of hydration. These results are 109%, 101%, and 48% respectively of those produced by HPC made without CFA.

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