Strength development of binary cement concrete, using Pulverized Fly Ash (PFA) under various curing conditions

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ABSTRACT

Binary Cement incorporating Supplementary Cementitious Material (SCM) is widely used in concrete to reduce the cement consumption in construction industry. Cement production is a major source for the emission of Green House Gases (GHG) and there is an increasing pressure to reduce its consumption to avoid further Global Warming and Climate changes etc. In this research, Pulverised Fly Ash was used to partially replace cement in the concrete. Three levels of replacement of cement by PFA were selected and the specimens were cured under summer and winter environments. The strength development characteristics of the blended concrete were compared with the control mix without PFA. The strength gain under winter curing condition was observed as slower. At water cement ratio of 0.35, concrete with 30 % replacement of cement by PFA achieved high early age strength. PFA concrete gained more strength than the PC concrete after the age of 28 days. The 28 days compressive strengths of blended concrete for 30 % of cement replacement by PFA has been observed as nearly the same as that of control concrete mix.

KEYWORDS

Supplementary Cementitious Material, Pulverized Fly Ash , partial replacement, compressive strength, Curing.

1. INTRODUCTION

According to the UNEP [1], the concept of sustainability has been known for a long period and there have been many conferences around the world in which governments and non-government organisations have participated to create awareness about the environmental impacts of modern developments. According to The Concrete Centre [2], the amount of embodied CO_2 (ECO_2) of concrete, is a function of the cement content in the mix designs. Hence more production of concrete will lead to more cement consumption and emission of CO_2 as a result. To reduce cement contents in concrete, various Supplementary Cementitious Material (SCM) are used which include Pulverized Fly Ash (PFA) as well.

Sustainable Development was defined by Brundtland Commission [3] in 1987 as "the development that meets the needs of the present without compromising the ability of future generations to meet their own needs". The extensive emission of Green House Gases (GHG), due to industrialization and use of fossil fuels in automobiles has led to Global Warming, Climate Changes (CC) and other environmental degradations, which has further intensified the need for sustainable development [4]. Embodied CO_2 (ECO_2), is the measure of the amount of CO_2 emissions generated from the energy needed for the raw material extraction, processing, transportation, assembling, installation, disassembly and deconstruction for any system over the duration of a product's life. The ECO_2 of the construction material is the highest one. For example, ECO_2 for cement is 913 Kg/tonne [5]. There is a general understanding that one tonne of cement production leads to almost one tonne of CO_2. At the other hand, concrete as construction material has been one of the major input for socio-economic development of societies and it consumption would continue. It is the second largest used material after water and it stand at two tonne per capita per year at global average[6].

To end poverty, protect the planet, and ensure prosperity for all, as part of new sustainable development agenda, different countries of the world adopted a set of goals on September 25th , 2015. Each goal has specific targets to be achieved over the next 15 years. To combat climate change and its impacts is one of the important goals of the sustainable development goals. (SDG). The SDG are comprised of 17 goals and 169 targets, which address the social, economic and environmental dimensions of development. The SDG goal 9, is based on Industry, Innovation and Infrastructure, which also demands robust and resilient infrastructure by retrofitting the existing one and construction of new one in the developing and Least Developing Countries (LDC). Hence the construction industry has to grow, exponentially with the demand for new infrastructure. The cement consumption as a result would also increase manifold leading to more Green House Gases (GHG) emissions in times to come. To offset the detrimental impacts of cement production, the research for exploring more Supplementary Cementitious Material (SCM) as partial replacement of cement would continue with more rigor in future [7]. To offset the negative impacts of the cement production on environment and reduce the cost of concrete, construction industry and concrete technologist around the world have been attempting to explore cementitious and pozzalonic material. In this context, Ground Granulated Blast Furnace Slag (GGBS) and Pulverized Fly Ash (PFA) have been extensively used during last two decades. Nailk and Ramme [8,9], used various mix proportions of fly ash added concrete for various levels of substitutions and reported the optimum level up to 55 % to achieve the concrete with 28 days compressive strength in the range of 35MPa. Poon [10] used Low Calcium High Volume Fly Ash (HVFA) for high strength concrete and achieved a 28 days compressive strength of 83 MPa. The high loss on Ignition (LoI) value for Fly Ash severely affects the compressive strength and creep of concrete when used as replacement of cement in concrete. The un-burnt ash particles increase the water requirement and reduce the compressive strength as well. To reduce this impact, High Range Water Reducers (HRWRs) have been used [11-12]. Huang C.H *et al* [13] developed a rational mix design method for concrete having 20 - 80 % replacement of cement by HVFA. They reported significant increase in the compressive strength of HVFA blended concretes at later ages such as 90 days and onwards.

According to Higgins [14], UK uses about two million tonnes per year of GGBS as cement and in UK 500,000 tonnes of Fly ash is used as cement addition per year and uses 100,000 tonnes of Fly ash as a component of blended cement. In China, about 15 million tonnes of GGBS is used per year [15]. According to the information given in the United Kingdom Quality Ash Association (UKQAA) (2004), PFA is a by-product obtained at power stations and is a solid material extracted by electrostatic and mechanical means from flue gases of furnaces fired with pulverised bituminous coal. It is carried by the exhaust gases and recovered as fly ash with fine particles. According to Thomas [16] the use of fly ash as supplementary cementing material in concrete has been known from the start of last century but the first research in fly ash was conducted at the university of California by Davis *et al* [17], and the first significant utilization of fly ash in concrete began with the construction of the Hungry Horse Dam in Montana in 1948. The production of the material has been changed to reduce the gaseous emissions in recent years but has not affected the nature of PFA except it has increased the loss on ignition (LOI). The standards and specification of PFA are covered under BS EN 450-1(2012) [18] and ACI-committee 226 [19].

PFA has been used widely as cementitious material in construction industry. Dhir *et al* [20] found that PFA fineness affects the strength of concrete and the strength of PFA concrete is reduced by using coarser PFA. In order to take care of the effect of PFA fineness on strength, they developed a simple procedure of varying the water content, cement content or both. Kayali and Ahmed [21] prepared concrete mixes by replacing PC with different percentages of Fly ash. The water/cement ratio was 0.38 for all the concrete mixes and the total amount of cementitious material content was kept constant for all the mixes and was equal to 450 kg/m^3. The concrete samples were cured with fog for seven days and then they were air dried till the age of 28 days for testing. They reported that there was a decrease in the compressive strength of concrete made with fly ash and this decrease was increased with the replacement level of fly ash. In the Angel Building, London, self-compacting concrete with 36 % fly ash, was used to eliminate the need for conventional methods of compaction, such as vibrating pokers. By using PFA, workability of concrete was improved around difficult interfaces and the light grey colour of PFA concrete added towards the aesthetic of the building. According to Neville [22], creep of GGBS and PFA concrete is lower than the CEM-I concrete, if cured in an environment where there is no moisture loss. Fly ash has been extensively used a partial replacement to cement in concrete, firstly to reduce the cement consumption in concrete and thereby making it relatively sustainable material and secondly increasing the mechanical properties of concrete in fresh and hardened forms [23]. The environmental considerations of High volume Fly Ash (HVFA) and its contribution to develop green & sustainable concrete have been researched extensively [24, 25].

1.1 EFFECT OF CURING ON STRENGTH OF FLY ASH CONCRETE.

The curing process also affects the properties of concrete made from ordinary cement or blended cement incorporating PFA. The water curing was found more effective than heat curing [26-27]. The slow steam curing of PFA added concrete has gained strength more than water and air cured specimen [28]. Safan & Kohoutkova [29] reported that continuously water-cured concrete specimens provided a better rate of strength development compared to other curing conditions and the compressive strength affected by drying condition varies at different ages. Zhang et al [30] checked the influence of curing temperature on the compressive strength of Fly ash based Geo-polymer Concrete (FAGC). The fly ash concrete specimens were cured under different curing conditions. The author concluded that high temperature is vitally important for specimens to gain higher compressive strength, especially the early strength. The specimens cured at room temperature for one day and then cured at high temperature had higher strength than that of directly cured at high temperature. Ki-Bong & Takafumi [31] concluded that the compressive strength of concrete specimens cured in water at 20 °C were higher than those of the sealed specimen. At low water cement ratio there is a possibility of self-desiccation of concrete and there are limitations on continued cement hydration, which explains the difference in strength between concrete specimens. External water is required to enable hydration to continue uninhibited. The strength development of concrete made under winter weather conditions (9 ^{o}C) was found faster than that of concrete made under summer conditions (20 ^{o}C), both for the standard and sealed specimens. For fly ash concrete (40 % fly ash) the strength of the specimens made under winter conditions was lower than those made under summer conditions.

In this research, the effects of the partial replacement of cement with PFA on strength development of concrete under different curing condition have been studied. The use of PFA in concrete tends to slow down the early age strength which limits its use in the fast track construction and post tensioned concrete, which are subjected to high early loads. Early age strength of concrete containing PFA can be increased by reducing the water/cement ratio.

2. RESEARCH SIGNIFICANCE

There is limited research work undertaken on effect of compressive strength and strength development characteristics of concrete incorporating PFA under various curing conditions. The non-uniform physical properties of PFA found in various parts of the world also affect the performance of concrete produced. It is expected that the results of the research will add to the existing data on use of blended cement in concrete and its performance under various curing conditions. The early age strength of blended concrete is relatively less than the normal concrete, which restricts its use in many important projects. Based on various trials mixing, the optimal level of water cement ratio, chemical admixtures and replacement of cement by PFA has been established under various curing conditions. This will help in further research to standardize, the properties and mixing of the concrete made with blended cements.

3. EXPERIMENTAL PROGRAM

3.1 Material

3.1.1 Pulverised Fly Ash (PFA)

PFA conforming to BS-EN 450-1 [32], was used as binary cement component in the production of concrete. PFA used in the concrete is commercially available in the UK and is classified as CEM IV according to BS EN 197-1 (2011) [33].

3.1.2 Portland cement

Ordinary Portland cement (OPC) used conformed to BS EN 197-1 [33] and was classified as CEM-I. The Portland cement was stored in the laboratory to avoid exposure to humidity.

3.1.3 Superplasticiser (SP)

High performance liquid superplasticizers conforming to BS-EN 934-2 [34] was used to achieve the required workability.

3.1.4 Aggregates

Graded natural sand with a maximum particle size of 5 mm and complying with the requirements of BS EN 12620-1 (2009) [35], was used as fine aggregate in the concrete mixes. Thames valley natural aggregates of average 12.5 mm were used as coarse aggregate in the concrete mixes. The maximum size of the aggregate used was 20 mm.

3.1.5 Concrete Mix Proportions

Trial mixes of concrete were designed to achieve an equal 28 days compressive strength of 40 MPa and the strengths of 10 MPa after 16 hours and 25 MPa after 38 hours to meet the practical requirement of post tensioned concrete beams. The trial mixes are shown in Table 1 and 2. To achieve a practical level of workability and cohesion, suitable for pumping, concrete was designed for a target slump of 200 mm. The overall maximum water/cement ratio was maintained at 0.45 and overall minimum cement content at 340 kg/m^3. Superplasticiser was used to minimise water and cement contents to achieve low free w/c ratio.

Table 1 Concrete Mix proportion

3.1.6 Test Samples and testing procedure:

Two batches of concrete were made for each concrete mix, to cast samples. Sixty 100 mm x 100 mm cubes were cast for each mix to measure the compressive strength development according to the British standard test method (BS EN 12390) [36], at the age of 1,2,3,5,7,14,28 and 56 days cured under different curing regimes.

Two cube specimens from each mix and curing regime were tested for compressive strength using an Avery Denison 2500 kN machine as shown in Figure 1. In the case of more than 10 % difference in two results a third specimen was also tested. The concrete samples cured under the regime C3 were dried at room temperature for three hours before testing. The specimens were loaded at a rate of 0.4 N/s until failure, following the method described in EN 12390-3 (2009) [21].

Figure 1 Compressive strength Test using Avery Denison 2500 kN machines.

3.1.7 Curing Environments

Engineering performance of concrete cured under three different regimes was recorded. The following three methods were chosen for curing the concrete which have a close resemblance with the onsite curing environment in the UK.

3.1.8 Summer Curing Environment (C1)

After casting concrete in the moulds, it was stored for 24 hours at a laboratory temperature of about 20 ± 2 °C and covered with plastic sheets to minimize the loss of moisture. After 24 hours concrete was demoulded and sealed in air-tight plastic bags so that there is no loss of moisture and stored at a laboratory temperature of 20 °C. This curing environment has been titled as C1 and shown in Figure 2 (a).

3.1.8 Winter Curing Environment (C2)

After casting concrete, it was stored for 24 hours with in the moulds in the environmental chamber controlled at a temperature of 7 °C and 55 % relative humidity which resembles the normal winter temperature in the UK. Moulds were covered with plastic sheets to minimize the loss of moisture. After 24 hours, concrete was demoulded and sealed in the air-tight plastic bags to avoid any loss of moisture and stored in the environmental chamber controlled at 7 °C. Concrete cubes cured under the C2 curing environment as shown in Figure 2 (b).

3.1.9 Water Curing Environment (C3)

After casting concrete in the moulds, it was stored at a laboratory temperature of 20 °C and was covered with plastic sheets. After 24 hours, concrete was demoulded and was immersed in the water chamber controlled at a temperature of 20 ± 2 °C. Concrete stored under curing environment C3 is shown in Figure 2 (c).

Figure 2 . Concrete specimens under various curing environment

4. RESULTS & DISCUSSION

The strength development of various concrete mixes cured under, two curing conditions C1 and C2 are shown in Table 2. The compressive strengths of PFA concrete under water curing all the curing conditions are given in Table 3. The strength development characteristic of different mixes of concrete under the three regimes are shown in Figure 3, 4, 5 for control mix, 90PC/10PFA, 80 PC /20PFA and 70 PC /30PFA respectively.

Figure 3 Compressive strength development of 100PC-Control concrete mix under various curing conditions.

Figure 4 Compressive strength development of 90PC/10PFA concrete mix under various curing conditions.

Figure 5 Compressive strength development of 80PC/20PFA concrete mix under various curing conditions.

4.1 Strength development of blended concrete with PFA:

Strength development of various PFA concrete mixes and 100 PC control mix, cured under curing regime C1 are compared in Figure 6. Following findings were noted.

- The compressive strength of PFA concrete mixes cured under regime C1 (cured in sealed plastic bags at 20 ^oC) are slightly less than those cured under regime C3 (cured under water at 20 ^oC). It is concluded that there is a close correspondence in the compressive strength of the specimens cured in sealed plastic bags for minimising the loss of moisture and concrete specimens cured under water at the same temperature of 20 ^oC.
- The winter curing environment at 7 ^oC (C2 curing environment) has affected the strengths of all the concrete mixes including 100PC-Control concrete mix but has reduced the strength of PFA concrete more than the 100PC-Control concrete mix. In winter it is recommended that the curing temperature of the PFA concrete be kept at least 20 ^oC at early ages to gain enough strength to be used in the fast track construction and to enhance the long-term strength of PFA concrete, an extended curing time is required.

Figure 6 Compressive strength development of 70PC/30PFA concrete mix under C1 curing conditions

PFA concrete has shown that the early age strength development is slow due to the apparent slow pozzolanic reactions between PFA and the lime ($Ca(OH)_2$) generated by the PC concrete. Under curing regime C1 the strength of 90PC/10PFA, 80PC/20PFA and 70PC/30PFA concrete mixes are 25.5 MPa, 25.5 MPa and 34 MPa respectively at the age of 3 day as compared to 33 MPa for the, 100PC-control concrete mix. At 14 days of age the strengths increased to 31.5 MPa, 38.5 MPa, 46 MPa and 46.5 MPa respectively. At 28 days of age, these strengths are further increased to 41MPa, 42.5 MPa, 55 MPa and 51.5 MPa respectively. The difference in the compressive strengths at 28 days for PFA concrete and 100PC concrete is relatively less. For 70PC/30PFA at w/c ratio of 0.325, the blended concrete has achieved the maximum 56 days compressive strength of 65MPa under curing condition C1, as compared to 57.5 MPa for 100PC with no Fly Ash. The strength gain in PFA concrete is maximum during 28 and 56 days of age. The strength development of PFA added blended concrete for various of cement replacement, under various curing conditions is also shown as % of the control mix with no PFA, in Table 4 . The comparison in Table 4, shows that 33% replacement of cement by PFA, gives the best results under all curing conditions. The compressive strengths of such concrete are either equal to that of control mix, where no PFA has been used or even greater.

Table 4 Comparison of Compressive Strength of blended concrete for various level of replacement of cement with PFA and Control mix with no PFA at the age of 28 & 56 Days

1.5.2 Strength development of concrete under various curing conditions

Strength development of PFA concrete mixes are compared with the PC concrete mix cured under regime C1 (20 °C) in Figure 7 and cured under regime C2 (7 °C) in Figure 8.

- The compressive strength for all ages of concrete under winter conditions of curing is less. Hence low winter temperature (7 °C) has severe impact on compressive strength and the concrete temperature needs to be maintained at min summer temperature of 20. The compressive strength gain under water curing conditions C3 is however, the maximum in all cases.

Figure 7 Comparison of compressive strength development of PFA concrete for C1 curing condition

Figure 8 Comparison of compressive strength development of PFA concrete for C2 curing condition

- The 28 days compressive strength for 70PC/30PFA mix under C1, C2 and C3 are 55 MPa, 44 MPa and 56.5 MPa respectively, which shows that there is no much difference in strength gain under C1 and C3 conditions. For mix 80PC/20PFA, the values are 42.5, 34 and 42.5 MPa respectively. For mix 90PC/10PFA, these values are 41, 31 and 43 MPa and for 100PC, the values under three curing conditions are 51.5, 46 and 53.5 MPa respectively. The comparison of values in Table 2 for 28 days show that the samples have gained almost the same strength under curing conditions C1 and C3 and 72 % - 82 % under C2 (winter conditions).

The strength gain between the ages of 28 days and 56 days are compared in Table 3 and expressed as percentage of 56 days strength of C3 curing conditions when the samples are cured under water. Here the strength gain in PFA concrete is relatively faster than the 100PC samples. This is in line with the general observations with the concrete having SCM, where the specified compressive strength is calculated at the age of 56 days instead of 28 days.

5. CONCLUSION & DIRECTIONS FOR FUTURE WORK

- Partial replacement of cement by PFA up to 30 % has little impact on the compressive strength at the age of 28 days when compared with samples having no PFA, as the compressive strength achieved has a reasonable value for use in structural works. This can offer greater opportunity for saving of cement and CO_2 emissions, thereby making concrete relatively sustainable.
- The strength development of PFA concrete is relatively slow in the beginning up to 7 days and then increases with relatively high rate. The optimum strength is achieved at 56 days instead of 28 days of age.
- The results shows that there are significant reductions in the rate of strength gain of concrete cured under winter curing conditions (7 °C), as compared to those of summer curing and under water (20 °C). In winter conditions at water cement ratio of 0.35 for concrete containing PFA up to 30 %, special care should be taken regarding temperature increase of the curing environment especially at the early age to gain

enough strength. This can be achieved at covering the concrete in sealed conditions. The heating of concrete buildings, to increase the temperature for curing is a common practice in cold areas.

- The strength development under the summer conditions and under water is almost the same for PFA concrete in which cement is partially replaced by 20 % and 30 %.
- From comparison of the compressive strength development of PFA concrete results between the ages of 28 and 56 days, it is evident that the strength gain is relatively more during this period as compared to the 100 % PC concrete with no PFA. It is more advisable to use the specified strength of PFA concrete at 56 days, as already suggested by earlier research on the blended concrete.

For future work it is recommended.

- To check the effects of extreme summer temperature on strength development of PFA concrete.
- To check the impact of curing temperature on normal strength concrete containing PFA.
- To estimate the environmental benefits associated with using PFA in concrete as a partial replacement of cement.

Acknowledgement

The would like to pay special thanks the Kingston University UK and the technical staff of Concrete and Materials laboratory , specially Mr Peter and Mr Howard who assisted during the experimental work.

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List of Tables:

List of Tables and Figures:

Figure 7 Comparison of compressive strength development of PFA concrete with Control mix under C1 curing conditions

Figure 8 Comparison of compressive strength development of PFA concrete with Control mix under C2 curing conditions

Table 1 Concrete Mix proportion

MIX PC/PFA	CONSTITUENT MATERIALS, Kg/m^3							Calculated Density (Kg/m^3)	Slump (mm)
	Free Water (Litres)	Binder (Kg/m^3)		Aggregates (Kg/m^3)		w/c ratio	Super plasticiser (ml/100kg of binder)		
		PC	PFA	Coarse	Fine				
100PC-control	160	457	-	1285	500	0.35	1200	2400	150
90PC/10PFA	150	360	40	1325	540	0.375	1200	2415	185
80PC/20PFA	150	370	92	1310	495	0.325	1200	2415	190
70PC/30PFA	150	324	138	1310	495	0.325	1200	2415	200

Table 2 Compressive strength development of various concrete mixes for summer environment C1 and winter environment C2 , expressed as % of 56 days strength

Age (days)/Compressive Strength (MPa)

Curing	**1 D***	**2 D**	**3 D**	**5 D**	**7 D**	**14D**	**28 D**	**56 D**	**Difference (MPa/%)**
	31%	47%	56%	78%	81%	88%	97%	100%	
100PC- control-375 kg/m^3@ w/c 0.40									
C1	*17*	25	33	41.5	45.5	46.5	51.5	57.5	6 (10%)
	30%	43%	57%	72%	79%	81%	90%	100%	
C2	*17*	24	27	35	36.5	39	46	51.5	
	33%	47%	52%	68%	71%	76%	89%	100%	
C3							51.5	58	
90PC/10PFA@ w/c 0.40									
C1	13	22	25.5	26.5	29	31.5	41	44.5	4 (9%)
	29%	49%	57%	60%	65%	71%	92%	100%	
C2	13	19.5	21	23	26	29	31	40.5	
	32%	48%	52%	57%	64%	72%	77%	100%	
C3							42.5	44	
80PC/20PFA@ w/c 0.35									
C1	16.5	24.5	25.5	28	30.5	38.5	42.5	46	4.5 (10%)
	36%	53%	55%	61%	66%	84%	92%	100%	
C2	16.5	19.5	21	25.5	27	31.5	34	41.5	
	40%	47%	51%	61%	65%	76%	82%	100%	
C3							42.5	44	
70PC/30PFA@ w/c 0.325									
C1	20	-	34	38.5	41	46	55	65	7 (10%)
	31%		52%	59%	63%	71%	85%	100%	
C2	20	-	28.5	30.5	34	40.5	44	58	
	34%		49%	53%	59%	70%	76%	100%	

*. The representative samples under C1 and C2 are de-moulded after one day and tested. Hence the compressive strength of the samples are treated same at age of 1 day.

Table 3. Compressive Strength at the age of 28 & 56 Days cured under various curing regimes

Concrete Mix	Test Age days/Comp Strength (MPa)					
	28 days			56 days		
	C1	C2	C3	C1	C2	C3
70PC/30PFA	55 97%	44 78%	56.5 100%	65 105%	58 94%	62 100%
80PC/20 PFA	42.5 100%	34 80%	42.5 100%	46 104%	41.5 94%	44 100%
90PC/10 PFA	41 95%	31 72%	43 100%	44.5 101%	40 91%	44 100%
100PC-Control	51.5 96%	46 86%	53.5 100%	57.5 99%	51.5 88%	58 100%

Table 4 Comparison of Compressive Strength of blended concrete for various level of replacement of cement with PFA and Control mix with no PFA at the age of 28 & 56 Days

Concrete Mix	Test Age days/Comp Strength (MPa)					
	28 days			56 days		
	C1	C2	C3	C1	C2	C3
100PC-Control	51.5	46	53.5	57.5	51.5	58
70PC/30PFA	55 107%	44 96%	56.5 106%	65 113%	58 113%	62 107%
80PC/20 PFA	42.5 83%	34 74%	42.5 79%	46 80%	41.5 80%	44 76%
90PC/10 PFA	41 80%	31 67%	43 80%	44.5 77%	40 78%	44 76%

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Figure 1 Compressive strength Test using Avery Denison 2500 kN machines

a. Summer curing condition C1

a. winter curing Environment (C2) c. water curing environment (C3)

Figure 2. Concrete specimens under various curing environment

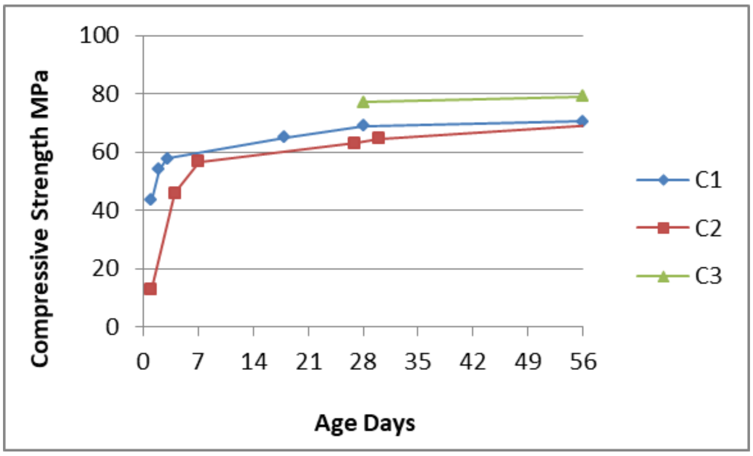

Figure 3 Compressive strength development of 100PC-Control concrete mix

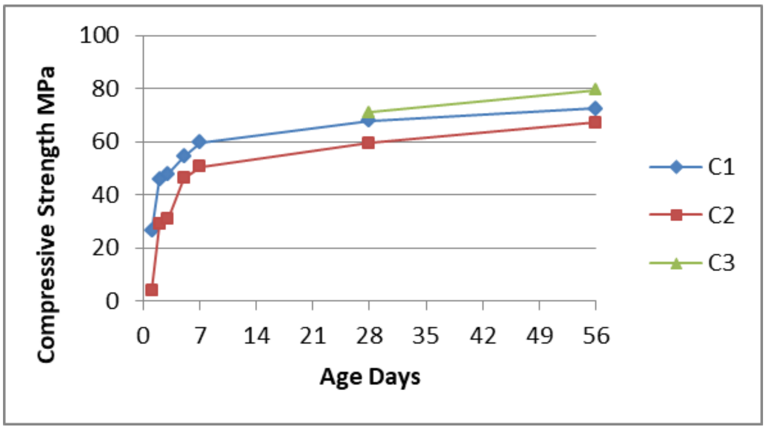

Figure 4 Compressive strength development of 90PC/10PFA concrete mix

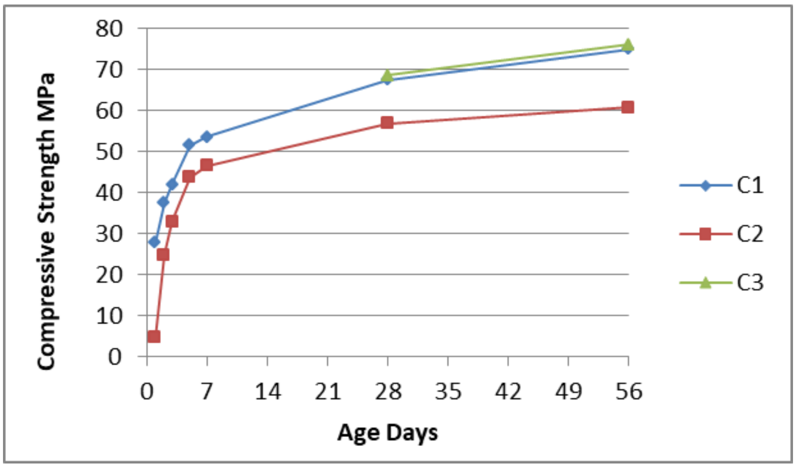

Figure 5. Compressive strength development of 80PC/20PFA concrete mix

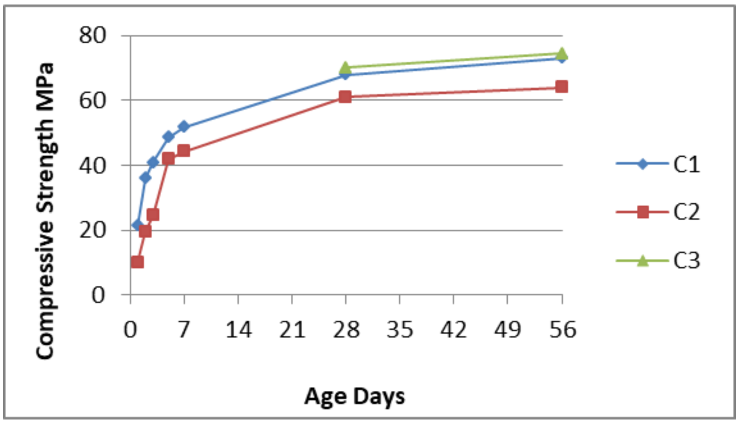

Figure 6. Compressive strength development of 70PC/30PFA concrete mix

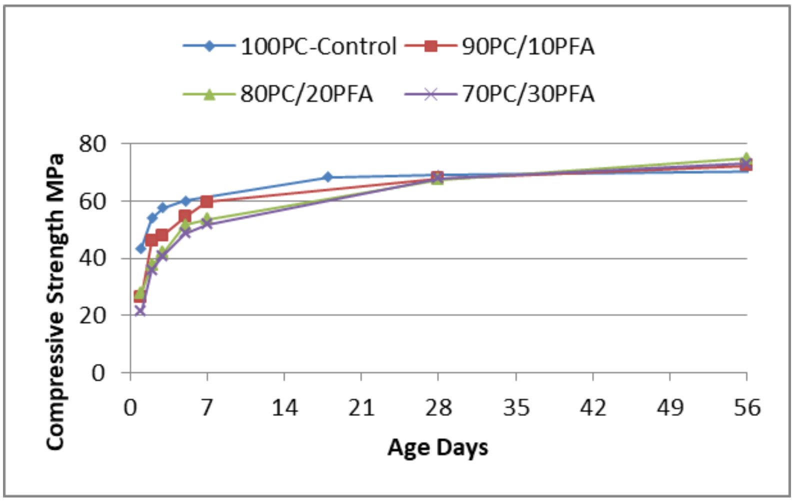

Figure 1 Compressive strength development of PFA concrete for C1

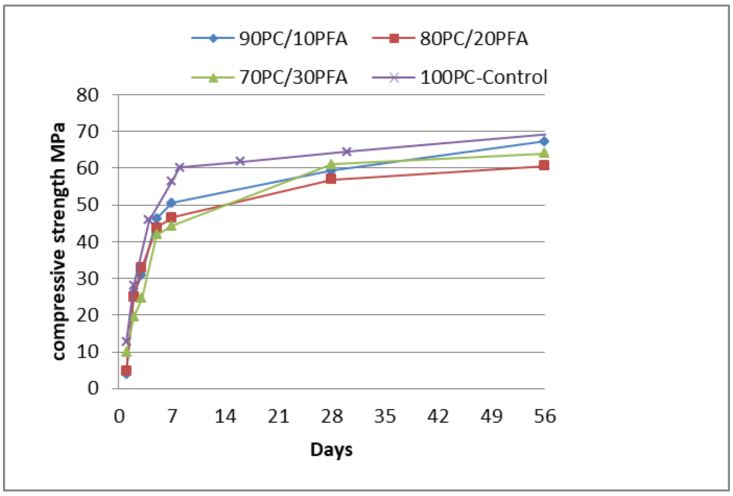

Figure 8 Compressive strength development of PFA concrete mixes for C2