PFA 함유량이 높은 콘크리트의 강도발현에 관한 연구
Research on Strength Development of High PFA Concrete

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요 약

콘크리트의 압축강도는 구조물 설계의 기본 요소이며, 압축강도의 증진전개 과정을 통하여 전반적인 시멘트와 콘크리트의 특성을 알 수 있다. 실험결과에 의하면 애쉬(OPC/PFA) 콘크리트는 일반적으로 보통(OPC) 콘크리트보다는 낮은 조기강도를 보여 주었으며(콘크리트 타설 후 28일전까지), 그리고 압축강도의 차이점은 콘크리트에 섞은 PFA의 양이 증가할수록 더 커졌다(애쉬에 의한 시멘트 대체량은 15%, 30% 그리고 45%). 그러나 비록 높은 비율의 애쉬량을 콘크리트에 사용했어도(대체량 45%) 조기강도 시멘트를 사용한 애쉬(RHPC/PFA 45) 콘크리트의 조기강도는 보통 콘크리트와 비슷한 강도를 보여 주었다. 28일에서 3년까지의 강도실험에서는 애쉬 콘크리트가 포졸라닉(pozzolanic) 영향에 의하여 보통 콘크리트 보다 항상 높은 강도를 보여 주었다. 보통 양생온도 조건보다 높거나 낮은 온도에서는(5℃ 그리고 50℃) 애쉬 콘크리트가 항상 높은 압축강도를 나타내었다. 그러나 건조 양생시 낮은 양생온도 조건에서는 보통 콘크리트가 더 높은 압축 강도를 나타내었다.

ABSTRACT

The strength development of PFA concretes were investigated in this study. The work undertaken was divided into two parts which considered both the influence of PFA replacement level up to 45% and the effect of cement type at the high PFA level(45%). The additional cement considered included a rapid-hardening portland cement. The full range of concrete structural grades were studied and eight curing conditions covering those used in practice were examined. The early strength reduced with increasing PFA content. However, post 28 days, the reverse was observed. It was possible through the use of rapid hardening portland cement at the high PFA level to achieve similar early strength to OPC concrete, with the same benefits noted above also being obtained post 28 days. The compressive strength of high PFA content concretes at high temperature was found to be higher than the control at all ages both in water and air. The same trends were observed at low temperature in air. However, the reverse occurred at the low temperature in water.

Keywords : PFA(Pulverised Fuel Ash), strength, binder, workability, replacement level, grade, pozzolanic reaction, curing, ages, temperature

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1. Introduction

Cementitious materials have been used for a range of applications from ancient times to modern construction. However, since the invention of Portland cement in 1824, concrete has become the most widely used construction material in the world. In recent years there has been an increase in the use of pozzolanic materials as partial replacements for a portion of the Portland cement content of concrete[1]. In particular, these include materials produced as by-products from manufacturing or industrial processes eg. pulverised-fuel ash(PFA), ground-granulated blastfurnace slag(GGBS) and micro-silica(MS).

The use of PFA as a cement replacement material in concrete was first considered in 1914[2] and later by Davis et al(1937)[3] who reported the first major study of PFA for use in concrete. A great deal of effort world-wide has been devoted to exploring the properties of PFA and how they influence the properties of the resulting concrete. It was found that PFA offers significant technical and economic benefits, and these range from improvement in concrete workability and fresh properties though to ultimate strength development and long term durability performance[1]. Since 1970 the electric power stations generated by coal has been increased due to the increasing price of oil. So the by-products of PFA was also increased in the world. However, the use of PFA as a construction material in Korea recorded about 10% of total products which is relatively lower than the industrial countries (27% in USA and 47% in Japan)[4].

The strength of concrete provides a good indication of overall quality and is generally considered to be its most important property. The strength development of PFA concrete is governed by its mix proportions, the chemical and physical characteristics of PFA, reactivity, curing condition and age[5,6]. Since PFA is normally incorporated with ordinary portland cement, PFA concrete has offered significant benefits for the long term strength due to the pozzolanic reaction[7]. However, this reaction leads to the retard effect at early hydration of concrete, consequently the PFA concrete may have a reduced early rate of strength development[8].

To overcome the lower early strength, PFA has been blended with rapid-hardening Portland cement(RHPC) and this approach has been used, for example, in fast-track concrete pavements[9] and precast concrete manhole units[10]. Although the RHPC/PFA concrete has been used in practice, the strength development of the concrete incorporating with high PFA contents has not been investigated on a mass quantative basis as an alternative to OPC concrete.

The objective of this study is to overcome the lower early strength of PFA concretes by means of using RHPC and having a excess amount of PFA based on the equivalent strength at 28 day. This will also increase the economic benefits of using high PFA content in concrete as a structural material. In line with this PFA could be used efficiently and it may encourage the increasing use of PFA in concrete construction in Korea. The study examined the strength development of concretes made with blends of OPC(up to 45% replaced by PFA) and concretes comprising RHPC(at a replacement level of 45%) were tested with different curing conditions and full range of concrete grades.

2. Experimental details

The work is carried out with various concrete grades(250, 350, 500, 600 and 700kg/cm^2) and with two different curing conditions(under water and air). In addition, 6 other curing environments were considered on selected 350kg/cm^2 concrete mixes in order to examine the effect of curing temperature on strength development(Table 1). All test were performed on 100mm concrete cubes, tested at ages of 3, 7, 14, 21 and 28 days, 3 and 9 months, and 1, 2 and 3 years, with 2 specimens in each case.

2.1 Materials

The binders used were two Portland cements to BS(British Standard) 12[11], an ordinary and a rapid-hardening. This was combined with a low-lime pulverised-fuel ash to BS 3892 : Part 1[12]. The main chemical and physical properties of these materials are given in Table 2.

The aggregates consisted of single size crushed rock(20mm and 5mm), crushed rock sand and a fine sand.

2.2 Mix proportions

The initial control mix proportions for the OPC concrete were designed according to the method which has been developed by Teychenne[13]. Mixes containing PFA contents of 15%, 30% and 45% were also designed according to this method. Trial mixes were carried out until the design strength at 28 days and required slump(75mm nominal) were obtained. The final mix proportions used are given in Table 3.

For the RHPC/PFA concrete the same proportions as OPC/PFA 45 were initially used and modified until achieving the required strength and workability. A number of trial

Table 1 Curing conditions

a) Water curing	
E1	Water 5℃
E2	Water 23℃
E3	3days water 23℃, thereafter air 23℃, 55% RH
E4	Water 50℃
b) Air curing	
E5	24hours air 5℃, 95% RH : 27days air 10℃, 55% RH thereafter air 23℃, 55% RH
E6	Air 10℃, 55%
E7	Air 23℃, 55%
E8	Air 50℃, 55%

Table 2 Properties of binders

Property	Binders		
	OPC	RHPC	PFA
Chemical composition, %			
SiO_2	21.2	21.0	47.8
Al_2O_3	4.2	5.0	30.7
Fe_2O_3	2.7	3.1	3.8
CaO	64.4	64.7	7.1
MgO	1.5	2.5	1.8
P_2O_5	0.1	–	–
TiO_2	0.2	–	–
SO_3	2.4	3.0	0.7
K_2O	0.2	0.8	0.8
Na_2O	1.3	1.3	0.4
MnO	0.1	–	–
LOI	1.9	1.1	1.3
Bogue compound composition, %			
C_3S	62.1	57.5	–
C_2S	14.0	16.7	–
C_3A	6.5	8.1	–
C_4AF	8.2	9.3	–
Mineral composition(%)			
Glass	–	–	83.4
Mullite	–	–	11.0
Quartz	–	–	2.2
Magnetite	–	–	1.3
Hematite	–	–	0.7
Physical properties			
SSA(m^2/kg)	322	490	–
RD	3.2	3.1	–

Table 3 Mix proportions of OPC and PFA concretes mixes

Concrete mix	Mix proportions, kg /m³								W/C Ratio
Design Strength (kg /cm²)	Cement	PFA	Total	Water	Aggregate			Total	
					Coarse	Sand	Filler		
OPC control									
250	255	–	255	190	975	770	200	2390	0.75
350	305	–	305	190	975	725	200	2395	0.62
500	385	–	385	190	1000	680	150	2405	0.49
600	440	–	440	190	1035	650	100	2415	0.43
700	510	–	510	190	1115	565	50	2430	0.37
OPC /PFA15									
250	215	40	255	175	1005	765	200	2400	0.69
350	265	45	310	175	1000	725	200	2410	0.56
500	330	60	390	175	1030	670	150	2415	0.45
500	380	65	445	175	1065	640	100	2425	0.39
700*	430	75	505	175	1135	565	50	2430	0.35
OPC /PFA30									
250	190	80	270	170	1025	730	200	2400	0.63
350	240	105	345	170	1025	660	200	2400	0.49
500	295	125	420	170	1050	670	100	2410	0.40
600*	345	145	490	170	1100	605	50	2415	0.35
700*	375	165	520	170	1185	520	–	2415	0.31
OPC /PFA45									
250	170	140	310	165	1140	785	–	2400	0.53
350	200	165	365	165	1140	730	–	2400	0.45
500*	270	220	490	165	1180	575	–	2410	0.34
600*	315	255	570	165	1230	455	–	2420	0.29
700*	350	285	635	165	1320	225	–	2345	0.26
RHPC /PFA 45									
250	160	135	295	170	1100	835	–	2400	0.58
350	195	160	355	170	1100	775	–	2400	0.48
500*	245	200	445	170	1100	695	–	2410	0.32
600*	290	240	530	170	1125	590	–	2415	0.32
700*	335	275	610	170	1200	440	–	2420	0.28

* Superplasticising admixture used.

mixes were necessary before the final proportions were fixed. The superplasticizer was used for the high concrete grades in order to keep the water content fixed. The mix proportions are also given in Table 3.

3. Results and Discussion

3.1 Effect of PFA content

Figure 1 shows the strength development of the OPC and OPC /PFA concrete series(15%, 30%, 45% of replacement level) under water curing. The results show that at early ages (pre 28-day), the increasing PFA content reduced slightly the strength by replacement level up 30%, but the differences were minor in a range of between 0 and 30kg /cm². A more reductions were observed between OPC /PFA 30 and OPC /PFA 45 concrete over the nange of between 5 and 50kg /cm², and at higher grade with earlier ages(3 and 7 days), the

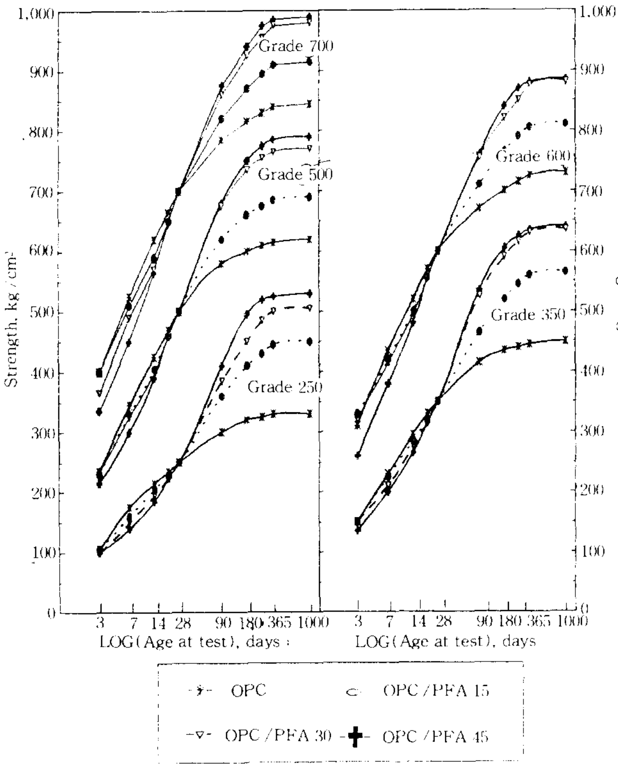

Fig. 1 Strength results of OPC/ PFA concretes, Curing : E2

differences were greater than those at lower grade with later gaes(14 and 21 days). The maximum differences in strength between OPC/PFA concretes prior to 28 days were generally exhibited at 7 days and thereafter decreased as the test age increased. It has been noted by many researchers[14] that the inclusion of PFA generally leads to a slower rate of strength development compared with OPC at early ages ; accordingly, PFA was regarded as having a "strength reducing effect"[15].

All mixes achieved the required 28 day design strengths, indicating that high PFA contents can be used in practice to achieve the full range of concrete strength grades. However, the potential difficulties with high PFA content concrete may be found in situations where early strength is critical. eg, early stripping of formwork or early load applications to the structure. Therefore, this represents a possible limitation over the use of this material in construction.

The OPC/PFA concretes have a significant benefit for the long term strength. Beyond 28 days the strength is increased with increasing PFA content and the maximum rate of strength development was noted between 90 days and 180 days. The PFA concretes exhibited higher strengths across range of grades and replacement levels of 40 to 195kg/cm² by 3 years. These results support previous studies which indicate that the maximum period of pozzolanic reaction takes place between 3 and 6 months[16]. It was suggested that later strength gains are associated with the filling of voids and water capillaries with reaction products leading to increasing homogeneity and nucleation of PFA concretes due to the contribution of pozzolanic activity[17]

3.2 Effect of cement

As noted above, the effect of increasing the PFA content of concrete, is to reduce early strength. This occurs even when the concrete is well cured and therefore represents a potential practical difficulty with binder. In order to boarden the study and provide a possible route to overcome this difficulty, it was decided to include additional cement/high PFA combinations. In the present study, rapid harding portland cement(RHPC) was used in an attempt to achieve parity of strength at early ages in 45% PFA concrete.

3.2.1 Water-cured

The strength development of high PFA concretes, pre-28 days, is shown in Table 4.

Table 4 OPC/ PFA 45 and RHPC/ PFA 45 concrete strength results, Curing : water 23℃

Concrete mix	Strength, kg /cm²				
Design Code Strength (kg /cm²)	Age at Test				
	3d	7d	14d	21d	28d
RHPC /PFA 45					
250	110	160	200	230	250
350	165	230	285	325	350
500	260	345	415	460	500
600	325	415	505	555	600
700	390	515	610	665	700
OPC /PFA 45					
250	95	140	185	225	250
350	135	200	265	315	350
500	215	300	390	460	500
600	280	380	475	555	600
700	335	450	555	650	700

The high PFA concretes containing rapid hardening portland cement had higher strength than those of OPC /PFA 45 concrete and the differneces in strength generally increased with increasing desing strength, but at 21 days the results obtained from the two concretes were very similar. It indicates that the retardation effect due to the PFA in early strength development may be compensated by using rapid hardening portland cement (RHPC).

A comparison between OPC and high PFA concretes is given in Figure 2. As indicated, the inclusion of the more active early strength cements in combination with PFA lead to there being very little difference between these and OPC concrete at early ages pre-28 day. Between 28 days and 3 years, the strength of high PFA concrete was always superior to the OPC control.

The strength development of high PFA concrete incorporating rapid hardening portland cement was closer to those of OPC concrete and was higher than those of the OPC /PFA 45 concrete at early ages. It has been

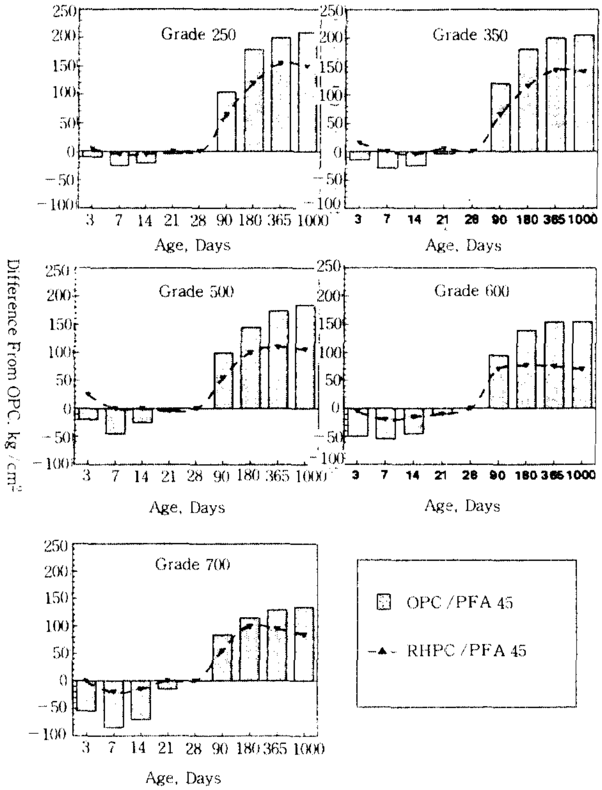

Fig. 2 Strength results of high PFA concretes shown as differences from the corresponding OPC concrete, Curing : E2

suggested that the use of PFA has a retardation effect which delays the early hydration. However, the use of RHPC cement, which is composed of finer particles than OPC cement, promote faster early rate of hydration and also increase concrete temperature. These effects tend to stimulate pozzolanic activity[18] and may compensate for the lag of early strength development of high PFA concretes. Therefore, the use of rapid-harding portland cement in concrete provide a route to overcoming problems associated with early strength development in high PFA content concrete.

As shown in this study, PFA when used in combination with OPC, shows a lower strength than OPC concrete at early ages, although it has very high strength in the long term. The use of RHPC indicate that the strength is similar to OPC concrete pre-28 days. Therefore, this work suggests that the RHPC /PFA 45 concretes may be used in mainstream structural engineering applications as a alternative material to OPC concrete and can be reliable in terms of strength. However, the OPC /PFA 45 may be utilised in concrete structures where early strength development is less critical such as mass foundations, large columns and dams, and slabs.

3.2.2 Air-cured

In practice, concrete structures are unlikely to receive standard curing, air-curing(E7) therefore was used to examine performance under condition closer to site curing. The strength results cured in air were lower than those cured in water at all ages and differences between these ranged from 55% to 65% at final test ages. It was suggested that in air curing the early stopping hydration due to the early moisture loss produce higher porosity of concrete and it also induces the drying shrinkage which may cause the microcraking. These effects cause the reduction of stength[19].

The results for OPC and high PFA concretes are given in Figure 3. This indicates that the OPC /PFA 45 concrete exhibited the lowest strength at low grades(250, 350 and 500kg /cm²) and at high grades the OPC concrete had inferior strength. But the RHPC /PFA 45 concrete had higher strength than other concretes at all ages and the differences increased with increasing concrete grades. This may be beacuse the concretes containing higher early strength cement reduced the evaporation of moisture from the surface due to the higher rate of hydration of the RHPC cement. This more efficient use of available water at the early stages and the higher heat of hydration, may accelerate the pozzolanic reation[20].

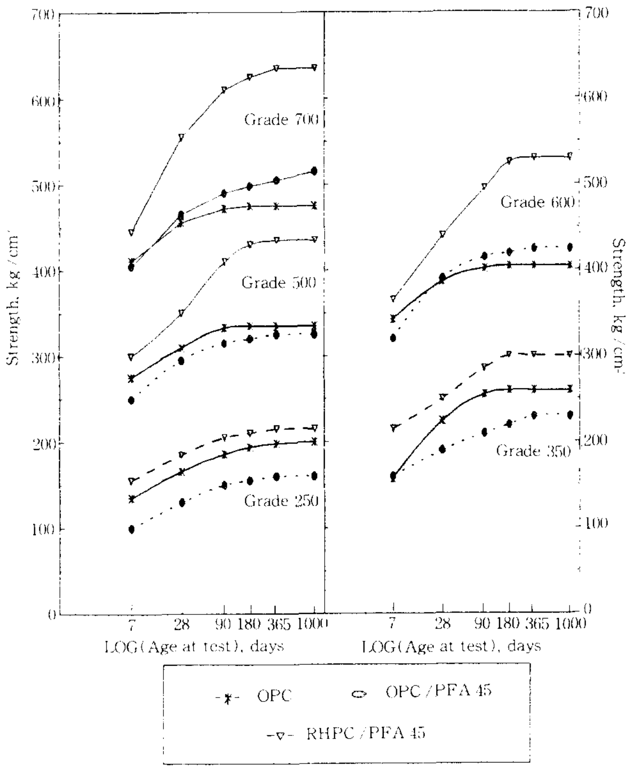

Fig. 3 Strength results of OPC/ PFA concretes, Curing : E7

3.3 Effect of Temperature

In practice, the environmental conditions in which concrete construction is carried out will be variable, and will depend on local climate and working conditions. In order to enable a full evaluation of the strength development of high PFA content concrete, a wide range of curing conditions were considered.

3.3.1 Water-cured

Comparison between the high PFA concretes and the OPC control(Figure 4) indicates that the former achieved higher strength, except at low temperature curing, E1, where they were lower than OPC at 28 days. This difference remained at 3 months, but reduced by 6 months.

It has been suggested that pozzolanic reactions of PFA are slightly more delayed at lower temperature, while they increase rapidly at high temperature[21] and this early pozzolanic activity due to the high temperature improves the strength of PFA concrete. It was also thought that the higher binder content of high PFA concrete may produce a strong and dense concrete due to the pozzolanic reaction at later ages[16].

3.3.2 Air-cured

In general the differences of strength between curing temperatures or ages were lower than those cured in water, it was also noted that the strength results obtained under air curing were inferior to those cured in water irrespective of curing temperature typically of the order of 50%.

A comparison between the PFA concretes and the OPC control(Figure 4), indicated that the strength of these concretes as similar under all curing conditions with the exception of E8 curing where the PFA concretes had a higher strength. As found for water curing, PFA concrete had a lower strength at low temperature and had the highest strength at the elevated curing temperature. All concretes showed little chage in strength during the 3 to 6 month period.

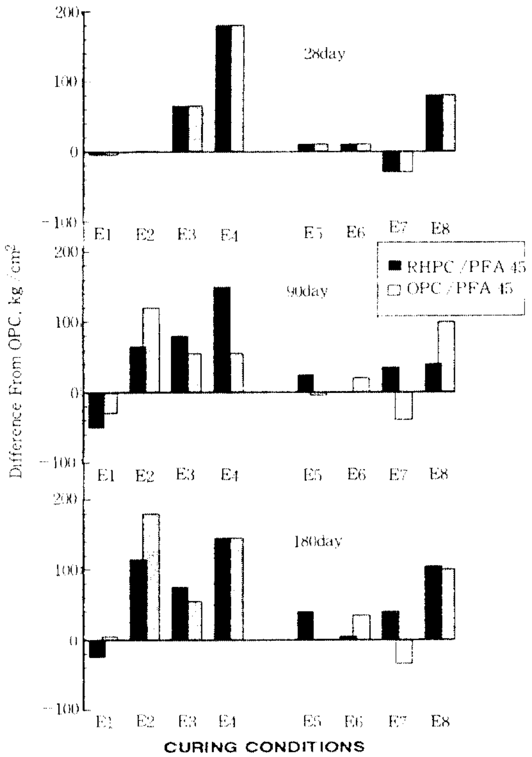

Fig. 4 Influence of cring temperature, relative to OPC concrete

4. Conclusions

Water-cured

1. Over the range of concrete strength grades, the strength of OPC/PFA concrete mixes were reduced with the increasing PFA replacement pre 28-day. However, the reverse was found beyond this age.

2. High PFA concretes containing rapid hardening portland cement under water-curing conditions exhibited similar or slightly reduced strength to OPC at early ages, but the strength of OPC/PFA 45 concrete was substantially lower than the corresponding OPC control. Beyond 28 days their strength was always superior.

Air-cured

3. The RHPC /PFA 45 concrete had similar strength to OPC concrete at early ages and marginally better in the longer term. OPC /PFA 45 concrete was inferior to OPC concrete at all ages with exception of the high grades of concrete post 28-day.

4. The RHPC /PFA 45 concrete was always of higher strength when compared to the OPC /PFA 45 concretes, both at early and later ages.

Temperature

5. The results for different water curing conditions indicated that the high PFA concretes generally had higher strength than OPC. However, at low temperature the high PFA concretes lagged OPC concrete.

6. At low temperature air curing high PFA concretes were similar to OPC at all ages. At high temperature the high PFA concretes had higher strength to OPC concrete at all ages.

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