STRENGTH DEVELOPMENT OF HIGH PFA CONTENT CONCRETE

GEO REPORT No. 48

W.C. Leung & W.L. Tse

First published, June 1995

Prepared by:

Geotechnical Engineering Office,
Civil Engineering Department,
Civil Engineering Building,
101 Princess Margaret Road,
Homantin, Kowloon,
Hong Kong.

This publication is available from:

Government Publications Centre,
Ground Floor, Low Block,
Queensway Government Offices,
66 Queensway,
Hong Kong.

Overseas orders should be placed with:

Publications (Sales) Office,
Information Services Department,
28th Floor, Siu On Centre,
188 Lockhart Road, Wan Chai,
Hong Kong.

Price in Hong Kong: HK$60
Price overseas: US$10.5 (including surface postage)

An additional bank charge of **HK$50** or **US$6.50** is required per cheque made in currencies other than Hong Kong dollars.

Cheques, bank drafts or money orders
must be made payable to **HONG KONG GOVERNMENT**

PREFACE

In keeping with our policy of releasing information of general technical interest, we make available some of our internal reports in a series of publications termed the GEO Report series. The reports in this series, of which this is one, are selected from a wide range of reports produced by the staff of the Office and our consultants.

Copies of GEO Reports have previously been made available free of charge in limited numbers. The demand for the reports in this series has increased greatly, necessitating new arrangements for supply. Henceforward a charge will be made to cover the cost of printing.

The Geotechnical Engineering Office also publishes guidance documents and presents the results of research work of general interest in GEO Publications. These publications and the GEO Reports may be obtained from the Government's Information Services Department. Information on how to purchase these publications is given on the last page of this report.

A. W. Malone
Principal Government Geotechnical Engineer
June 1995

EXPLANATORY NOTE

This GEO Report consists of two Special Project Reports on the laboratory investigation of the strength development of high PFA content concrete.

They are presented in two separate sections in this Report. Their titles are as follows:

SECTION 1 : INTERIM REPORT ON A LABORATORY INVESTIGATION OF THE STRENGTH DEVELOPMENT OF HIGH PFA CONTENT CONCRETE

W.C. Leung & W.L. Tse

This report was originally produced in December 1993
as GEO Special Project Report No.SPR 14/93

FOREWORD

At the request of the Standing Committee on Concrete Technology (SCCT), the Public Works Central Laboratory (PWCL) of the Materials Division carried out an investigation on the strength development of high PFA content concrete. The main objective of the investigation is to compare the strength development of OPC concrete and PFA concrete, subject to various curing environments and durations, and derive correlations between the 28-day strength and the long term strengths.

This interim report presents the test results obtained from the concrete mixes investigated, up to a test age of 90 days.

The early stage planning of this investigation was carried out by Mr. P.C. Wong. Mr. W.C. Leung took over the management of the project in January 1993 and prepared this report in conjunction with Mr. W.L. Tse, the project engineer, who organised and supervised the testing with the assistance of Mr. W.P. Chan and Ms K.Y. Law. The casting, curing and testing of cubes were carried out by staff of the Concrete Unit in PWCL.

The report was reviewed by the Chairman of SCCT, Mr. R.H. Pilling, the undersigned, as well as other members of SCCT.

P L R Pang
Atg Chief Geotechnical Engineer/Materials

CONTENTS

1. INTRODUCTION

Pulverized fuel ash (PFA) is a by-product of the combustion of pulverized coal in electricity generating stations. Its use as a partial replacement of Portland cement in concrete is well established. In Hong Kong, a PFA replacement of up to 25% is permitted by the General Specification for Civil Engineering Works (Hong Kong Government, 1992). However, the use of PFA in concrete has so far been rather limited. This is due partly to the perceived slow reactivity of locally produced PFA and partly to the lack of information on the strength development of local PFA concrete.

In view of the potential advantages in using PFA in concrete, the Standing Committee on Concrete Technology (SCCT) in May 1992 awarded a research consultancy to City Polytechnic to carry out a study on PFA concrete. The main aim of the study is to compare the performance of PFA concrete produced using local PFA, with similar grades of Ordinary Portland Cement (OPC) concrete. The strength development of both types of concrete up to a period of 90 days will be compared. In addition, their shrinkage and creep characteristics will be investigated. The City Polytechnic research covers concrete with 15% to 25% PFA replacement for physical property comparisons, and mixes with 15% to 40% replacement for cost comparisons.

In late 1992, SCCT requested the Public Works Central Laboratory (PWCL) to conduct a parallel study to compare the strength development of OPC and PFA content concretes up to the age of one year. The principal objective is to derive correlations between the 28-day and the long term strengths of a range of mixes produced with up to 55% PFA replacement. The cubes are to be cured over a range of temperatures from 10°C to 75°C, and with selected durations of curing, so that the influence of the curing environment can also be assessed.

This interim report presents the PWCL's findings up to October 1993. The results of the laboratory investigation of high PFA content concrete up to the age of one year will be given in a separate report to be prepared in mid-1994.

2. DESCRIPTION OF TEST MATERIALS

2.1 Selection of Materials

In order to enable the test results of the PWCL and the City Polytechnic to be compared, the materials used in both studies were obtained from the same sources. The constituent materials were tested by the PWCL in accordance with the relevant British Standards specified in the General Specification for Civil Engineering Works (Hong Kong Government, 1992).

2.2 Cement

The cement used was Golden Eagle Ordinary Portland Cement, supplied by the China Cement Company at Tap Shek Kok. Physical and chemical property tests on each of the three deliveries used in the study were carried out. The test results, which are given in Table 1, show that the cement used has consistent properties.

2.3 PFA

The PFA was supplied in bags by the China Cement Company. The results of the fineness, moisture content and water requirement tests on each of the three deliveries used in the study are given in Table 2.

2.4 Aggregates

The coarse and fine aggregates were of granitic origin and were supplied by Asia Stone Company Limited, from the Lam Tei Quarry. Asia Stone also supplied the river sand from an unspecified source in China. Physical property tests were carried out on the three deliveries of aggregates. The test results are given in Table 3.

3. CONCRETE MIX DESIGN

The mix design for the study comprised an OPC concrete and four PFA concrete mixes with replacement percentages of 25%, 35%, 45% and 55% respectively. Grades 30 and 45 concretes were aimed for in the design, as these are the most commonly encountered concrete grades in Hong Kong. The target 28-day strength of the mixes was taken as the grade strength plus 8 MPa, and a target slump value of 75 mm was adopted. All of the mixes chosen allowed demoulding within 24 hours of casting.

Trial mixes were carried out with the cement content increasing from 300 kg/m^3 to 550 kg/m^3 at 50 kg/m^3 intervals and PFA percentages of 0%, 25%, 35%, 45% and 55% respectively. The trial mix results indicate that the compressive strength of concrete depends mainly on the water/cement ratio. The relationship observed between the 28-day compressive strength and the water/cement (w/c) ratio for the OPC and PFA mixes up to 55% PFA replacement is shown is Figure 1. For clarity, the data points have been omitted in the figure, which is intended to show the trends only.

The trials indicate that the higher the percentage of PFA replacement, the lower the water/cement ratio will need to be if the target 28-day strength is to be achieved. As the water/cement ratio was lowered, the workability of the PFA mixes was also lowered. In order to maintain the target slump of 75 mm for the PFA mixes, it was found necessary either to increase the cementitious content or use a superplasticiser. However, it was considered undesirable to use a high cementitious content in the mix as this would likely lead to the occurrence of thermal cracks and alkali-aggregate reaction. Therefore, it was decided to use a superplasticiser to achieve workability where required, keeping the cementitious content at a reasonably low level. The superplasticiser used was Super 20, which was supplied by W.R. Grace (Hong Kong) Ltd.

The mix proportions adopted together with the estimated cost per cubic metre of concrete are given in Table 4. The costs were calculated based on the unit costs of the constituent materials and represent the material cost only.

4. THE LABORATORY INVESTIGATION

4.1 Test Procedures

The cubes cast were stored in a range of curing environments and durations. All the cubes were soaked in water at 27°C for a period of 24 hours immediately before testing. The density and compressive strength of the cubes were determined in accordance with the procedures laid down in CS1 (Hong Kong Government, 1990).

4.2 Curing Environment

After the cubes were cast, they were stored for 24 hours in the laboratory at 25° ± 5°C before demoulding. After demoulding, the cubes were cured under the various curing environments described in Table 5. A total of eight curing environments were investigated in the study. The environments were chosen to simulate as far as possible a range of *in situ* curing conditions, including conditions of inadequate curing which may be encountered in practice. For example, curing environments E2 and E3 are intended to simulate concreting in cold weather, whereas E7 and E8 would simulate the conditions in mass concrete pours. Curing environments E4 to E6 would simulate the possible conditions where curing was insufficient. Curing environment E1 is the standard (27°C) water curing as specified in CS1 for compliance testing in Hong Kong.

4.3 Age of Testing

For each mix, three cubes were cast and cured under each of the curing environments and these were then tested at each of the following test ages: 28, 56 and 90 days. Further testing is to be conducted later at 180 and 360 days. Six additional cubes were cast and cured under environment E1. Three of these were tested at the age of 7 days to assess the early age strength of the mix. Another three were tested at the age of 28 days to provide additional data for the control test age.

4.4 Allocation of Cubes

Due to the limited capacity of the mixer in the laboratory, each mix required a total of twelve batches of eleven cubes to be made. In order to minimise the effect of batch variation, the cubes were allocated randomly such that at any test age, the three cubes to be tested would come from three different batches, whenever possible. A typical example of cube allocation (for mix M8: Grade 45 with 45% PFA replacement) is shown in Table 6.

4.5 TEST RESULTS

The density and compressive strength results for mixes M1 to M10 are given in Tables 7 to 16 respectively.

5. DISCUSSION OF TEST RESULTS

5.1 Consistency of Test Results

From the density and compressive strength results in Tables 7 to 16, it can be seen that for the same mix, the density and compressive strength of cubes subjected to the same curing environment and tested at the same age are reasonably consistent. Therefore, the batch variation is small if not negligible.

The small batch variation justifies the decision to take the arithmetic average strength of three cubes as the statistical mean compressive strength. A summary of the mean compressive strengths for mixes M1 to M10 is given in Table 17.

5.2 Basis of Analysis of Test Results

5.2.1 Normalisation

While the mean compressive strengths of mixes M1 to M10 under curing environment E1 are very close to the target strengths (as can be seen from the summary in Table 17), it is obviously not possible in practice to achieve the target strengths exactly. In order to permit comparison of the test results amongst the different mixes for each of the two grades of concrete, it is necessary to normalise the mean compressive strengths obtained. The normalisation was carried out by applying a factor N as defined below to each of the mean strengths under curing environment E1 in Table 17:

$$N = \frac{\text{28-day Target Strength}}{\text{28-day Measured Strength}} \qquad \text{------------- (1)}$$

For example, a factor N = 38/39 = 0.974 was applied to the results obtained at the different ages for mix M1. The calculated N factors for all the mixes are given in Table 18.

There is also a need to compare the results obtained under curing environment E1 with results obtained under other curing environments, for each mix. In order to do this, the following principle has been invoked: the strength realisation potential of a particular mix of concrete is the same irrespective of the environment under which curing is carried out. Take, for example, mix M1. There is a potential for the concrete cured under environment E2 to achieve a 28-day strength of 39.0 MPa if curing is carried out to environment E1. Hence, if all results obtained under curing environment E1 are normalised by a factor N = 38/39, than the same factor should be applied to all the results obtained under curing environment E2, if a meaningful comparison is to be carried out. This approach has been adopted and the mean strengths obtained for the different curing environments have been normalised using the factors given in Table 18. The normalised mean compressive strengths for mixes M1 to M10 are given in Table 19.

5.2.2 Calculation of relative strength percentages

In order to facilitate comparison further so that the relative speed of strength development of the various mixes in the two concrete grades can be readily appreciated, the normalised mean compressive strengths for each mix in Table 19 have been converted to relative strength percentages by dividing the values by the (28-day) target strength of the same mix:

$$\text{Relative strength percentage for a particular mix of a specified concrete grade} = \frac{\text{Normalised Mean Compressive Strength}}{\text{Target Strength (= Grade Strength + 8MPa)}} \quad \text{------- (2)}$$

The relative strength percentages calculated for mixes M1 to M10 are given in Table 20.

5.3 Strength Development of PFA Concrete

5.3.1 The early age strength development

The early age strength characteristics of a concrete can be observed from its 7-day strength. The 7-day strength results for the ten mixes cured under standard curing environment (i.e. environment E1) are shown in Figure 2. The results indicate that for mixes designed to achieve the same target strength at 28 days, the higher the percentage of PFA replacement, the lower is the 7-day strength.

For the Grade 30 mixes, the 7-day relative strength percentage decreases steadily from 67% for OPC concrete to 52% for PFA concrete with 55% replacement. For the Grade 45 mixes, the corresponding 7-day relative strength percentages are 76% and 55% respectively. Similar findings have also been reported by Cabrera & Butler (1990) on the study by China Light & Power Co. Ltd.

The above results demonstrate that for a given design strength, the replacement of OPC by PFA has a slight retarding effect on the early age strength of the concrete. The rate of gain in strength of the PFA mixes between 7 and 28 days was however higher than the OPC mixes so that at 28 days, both mixes achieved the target strength.

5.3.2 Long term strength development

While PFA has a retarding effect on the early age strength of concrete, it is beneficial to the long term strength development of the concrete. This is illustrated by the results shown in Figure 3 for the Grade 30 mixes.

Under standard curing environment (i.e. environment E1), the Grade 30 OPC concrete mix (M1) achieved a 10% gain in strength between 28 and 56 days. Thereafter, no significant further gain was observed up to 90 days.

Under the same curing environment, the PFA concrete mixes achieved a steady gain in strength: at the age of 56 days, a 15% to 24% strength gain above the 28-day strengths was recorded. At the age of 90 days, the post 28-day strength gain varied from 23% to 27%.

A similar pattern of behaviour can be observed for the Grade 45 mixes, as shown in Figure 4. In this case, the strength of the OPC mix (M2) reduced after reaching the age of 56 days while the PFA mixes continued to gain strength.

The continuous gain in strength with age observed so far is a characteristic of PFA concrete. The results of the study by China Light & Power Co. Ltd also indicate a strength gain of between 20% and 40% above the 28-day strengths at 90 days.

5.4 Influence of Curing Temperature on Strength Development

5.4.1 General

The influence of curing temperature on the strength of the various concrete mixes is best illustrated by comparing the 28-day, 56-day and 90-day relative strength percentages of the mixes. The results for the Grade 30 and 45 mixes are shown in Figures 5 and 6 respectively.

5.4.2 Influence of low curing temperature

The results indicate that for both grades of OPC concrete, a curing temperature as low as 10°C did not have a significant influence on the strength of the concrete, compared to standard water curing at 27°C. The optimum curing temperature appears to fall between 20°C and 27°C.

For the PFA mixes, as the percentage of PFA replacement in the concrete was increased, the 28-day strength reduced quickly when the curing temperature dropped below 27°C. The influence of the low temperature curing reduced with time: when the cubes attained an age of 56 days, virtually all of the results (with the exception of the Grade 30 mix with 55% PFA replacement) rose above the target strength.

The behaviour of the mixes suggests that in the cold season of Hong Kong, the use of high PFA concrete in thin structural sections may lead to an impeding effect on the early age strength development of the concrete.

It should be noted that in this investigation, low temperature curing was only applied for 3 days for the 10°C curing (environment E2) and 27 days for the 20°C curing (environment E3). The impediment to early strength development could have been more prominent if there was a prolonged period of low temperature curing.

5.4.3 Influence of high curing temperature

The strength of both grades of OPC mixes reduced significantly as the curing temperature was increased from 27°C to 75°C. This behaviour applies for cubes tested at all ages. At 75°C, the relative strength percentage fell to between 80% and 90%. It should be noted that in a mass pour, the hydration temperature usually rises to a peak of 70°C to 80°C (depending on factors such as mix details and ambient and placing temperature) between 24 and 72 hours after casting. This suggests that the strength of OPC concrete in a mass pour may not all reach the target strength.

For the PFA mixes, the optimum curing temperature appears to fall between 27°C and 50°C, depending on the age of the concrete. The 28-day strengths of cubes cured at 27°C were lower than those cured at 75°C, whereas the 90-day strengths of cubes cured at 27°C were significantly higher than those cured at 75°C. Unlike the OPC mixes, all the PFA mixes cured between 27°C and 75°C achieved their target strengths.

5.5 Influence of Duration of Curing on Strength Development

It was generally believed that PFA concrete is more sensitive to curing than OPC concrete and if not cured sufficiently, the strength development of PFA concrete will be severely affected. The early results from PWCL indicate that this may not be entirely correct. The influence of duration of curing on the strength development of the Grade 30 and Grade 45 mixes is shown in Figures 7 and 8 respectively.

As can be seen from the figures, none of the cubes subjected to air curing only (i.e. curing environment E4) achieved their target strengths. The OPC mixes only achieved 75% of their target strengths as compared to an average value of 70% for the PFA mixes. No significant improvement was observed up to an age of 90 days. This indicates that if the concrete is not cured properly, the strength development of both OPC concrete and PFA concrete will be similarly impeded.

For cubes subjected to 3 days of water curing (i.e. curing environment E5), the target strength was also not achieved at 28 days. The OPC mixes achieved a relative strength percentage of between 86% and 96% at 28 days and did not appear to gain any further strength up to an age of 90 days. In comparison, the PFA mixes achieved between 81% and 94% of their target strengths at 28 days and continued to gain strength so that at 90 days, all of the PFA mixes achieved their target strengths.

For cubes subjected to 7 days of water curing (i.e. curing environment E6), all of the mixes, with the exception of the Grade 30 OPC mix, achieved their target strengths by 90 days.

For cubes that have been cured properly as in environment E1, the beneficial effect of PFA becomes more prominent. The PFA mixes achieved an average strength percentage of 124% by 90 days as compared to 110% for the OPC mixes.

6. CONCLUSIONS AND RECOMMENDATIONS

In response to SCCT's request, the PWCL carried out a laboratory investigation of the strength development of high PFA content concrete. A total of ten concrete mixes and eight curing environments were included in the study. Altogether 1560 density and compressive strength tests were carried out on concrete cubes. Based on the results up to a test age of 90 days, the following conclusions can be drawn:

(a) For the two concrete grades investigated, the replacement of OPC by PFA has a slight retarding effect on the early age strength of the concrete. The 7-day strengths of the PFA concrete mixes with PFA replacement percentages between 25% and 55% were between 52% and 68% of 28-day strength, compared to a range of 67% to 76% for the OPC concrete mixes. These results are for the standard (27°C) water curing environment.

(b) Despite the reduction in early age strength, the PFA mixes gained strength rapidly and achieved target strengths equivalent to the OPC mixes at 28 days. Between the ages of 28 days and 90 days, the OPC mixes showed an additional strength gain of about 10% whereas the strength gain of the PFA mixes was between 17% and 27%.

(c) For the OPC concrete mixes, a curing temperature as low as 10°C (applied over a 3-day period) did not have a significant effect on strength compared to standard water curing at 27°C. However, for the PFA mixes, as the PFA replacement percentage was increased, the 28-day strength reduced quickly when the curing temperature dropped below 27°C. The influence of the low curing temperature reduced with time : virtually all cubes tested gave strengths higher than the target strength beyond 56 days. These results may have application in cold season concreting.

(d) The optimum curing temperature for the OPC mixes appears to fall between 20°C and 27°C; whereas for the PFA mixes, the optimum curing temperature falls between 27°C and 50°C, depending on the age of the concrete.

(e) The strength of the OPC concrete mixes reduced significantly (to below the target strength) as the curing temperature was increased from 27°C to 75°C. This suggests that the strength of OPC concrete in a mass pour may not reach the target strength. For the PFA concrete mixes, the target strength was achieved for a curing temperature of up to 75°C for virtually all the mixes. This suggests that a PFA concrete is less sensitive to a high curing temperature than an OPC concrete of the same design strength. These results may have application in mass pours.

(f) The OPC and PFA mixes which were not cured sufficiently showed a reduction in strength by a similar amount.

The above conclusions obtained for the concrete mixes produced using local PFA are generally consistent with the results of research carried out elsewhere on concrete produced using different PFA sources.

It is recommended that the investigation be continued, completing the tests for the mixes up to the age of one year so that the long term strength development behaviour of the mixes can be studied.

7. REFERENCES

Cabrera, J.G. & Butler W.B. (1990). PFA Concrete Studies (1988-1998) Principal Report. China Light & Power Co. Ltd, 91p.

Hong Kong Government (1990). Construction Standard - Testing Concrete (CS1: 1990). Two volumes, Government Printer, Hong Kong.

Hong Kong Government (1992). General Specification for Civil Engineering Works. Three volumes, Government Printer, Hong Kong.

LIST OF TABLES

Table 1 - Physical and Chemical Properties of Cement

Test	Unit	Sample No.		
		1	2	3
Physical Properties				
Density	kg/m^3	3120	3150	3130
Fineness (specific surface)	m^2/kg	335	360	355
Standard consistence	%	26.0	27.5	28.5
Initial setting time	min.	120	135	105
Final setting time	min.	170	215	105
Soundness (expansion)	mm	1.0	0	1.0
Concrete cube strength (mean 3 days)	MPa	36.5	37.0	40.0
Mortar cube strength (mean 28 days)	MPa	70.5	73.5	69.0
Chemical Properties				
SiO_2	%	20.9	20.7	20.5
CaO	%	65.2	64.3	65.1
Al_2O_3	%	5.5	5.3	5.4
Fe_2O_3	%	3.1	3.1	3.0
MgO	%	0.7	1.5	1.1
K_2O	%	0.33	0.48	0.38
Na_2O	%	0.10	0.14	0.10
SO_3	%	2.4	2.5	2.4
Insoluble residue	%	0.2	0.4	0.2
Loss-on-ignition	%	0.6	1.2	1.1
C_3A	%	9.2	8.8	9.3
Lime saturation factor	-	0.95	0.94	0.96
Total alkali (equivalent Na_20)	%	0.32	0.46	0.35

Table 2 - Fineness, Moisture Content and Water Requirement of PFA

Test	Unit	Sample No. 1	Sample No. 2	Sample No. 3
Fineness of PFA residue on 45 μm sieve	%	3.8	3.4	2.9
Moisture Content	%	0.1	0.1	0.1
Water requirement	%	98	99	99

Table 3 - Physical Properties of Aggregates

Test	Unit	Coarse Aggregates						Fine Aggregates					
		20 mm			10 mm			Rock Fines			River Sand		
		Sample No. 1	2	3	Sample No. 1	2	3	Sample No. 1	2	3	Sample No. 1	2	3
1. Particle size distribution (Percentage Passing) Size of BS Sieve (mm)													
37.5	%	100	100	100	--	--	--	--	--	--	--	--	--
20	%	92	95	97	--	--	--	--	--	--	--	--	--
14	%	41	42	64	--	--	--	--	--	--	--	--	--
10	%	12	9	20	100	99	100	--	--	--	--	--	--
5	%	1	1	3	16	27	12	100	100	93	100	98	100
2.36	%	1	0	3	4	2	1	76	81	60	94	85	93
1.18	%	--	--	--	--	--	--	53	60	45	77	66	74
0.6	%	--	--	--	--	--	--	39	44	35	49	40	44
0.3	%	--	--	--	--	--	--	28	32	27	21	13	13
0.15	%	--	--	--	--	--	--	18	22	18	3	2	1
2. Flakiness index		17	17	17	20	--	19	--	--	--	--	--	--
3. Elongation index		38	37	38	9	--	3	--	--	--	--	--	--
4. Ten per cent fines value	kN	150	210	210	*50	--	--	--	--	--	--	--	--
5. Crushing value	%	23	20	--	*21	--	--	--	--	--	--	--	--
6. Water absorption	%	0.6	0.5	0.5	0.7	0.7	0.6	0.8	0.9	0.8	1.1	0.4	0.7

Legend : * The aggreggates used in these tests were of non-standard size with a size range of 6.3 - 10 mm.

Table 4 - Mix Proportions and Estimated Cost per Cubic Metre of Concrete

Mix Ref. No.	Grade	Nominal Percentage of PFA Replacement (%)	Total Cementitious Content (kg)	Cement (kg)	PFA (kg)	Water (kg)	Ratios		Admixtures		Slump (mm)	Cost per m^3 ($)
							A/C	W/C	D-17 (c.c.)	Super 20 (c.c.)		
M1	30	0	310	310	0	189	6.13	0.61	0	0	75	284
M3	30	25	330	248	82	178	5.73	0.54	0	735	80	276
M5	30	35	340	221	119	177	5.54	0.52	0	2100	70	285
M7	30	45	390	215	175	176	4.71	0.45	0	2155	75	290
M9	30	55	460	207	253	184	3.82	0.40	0	2449	65	297
M2	45	0	375	375	0	195	4.88	0.52	190	0	75	313
M4	45	25	390	293	97	168	4.72	0.43	0	1684	65	310
M6	45	35	400	260	140	168	4.58	0.42	0	3325	65	320
M8	45	45	460	253	207	175	3.84	0.38	0	2938	70	319
M10	45	55	550	248	302	187	3.03	0.34	0	4114	65	341

Notes : The unit costs listed below were used in calculating the cost per m^3 of concrete.

Cement	**$500/tonne**	**Sand**	**$70/tonne**
PFA	**$165/tonne**	**Fines**	**$60/tonne**
20 mm Agg	**$70/tonne**	**D-17**	**$5.5/litre**
10 mm Agg	**$70/tonne**	**Super 20**	**$12.8/litre**

Table 5 - Curing Environments of Cubes after Demoulding

Curing Environment	Description
E1	27°C water curing for 27 days, then air curing
E2	10°C water curing for 3 days, followed by 20°C water curing for 24 days, then air curing
E3	20°C water curing for 27 days, then air curing
E4	Air curing
E5	27°C water curing for 3 days, then air curing
E6	27°C water curing for 7 days, then air curing
E7	50°C water curing for 7 days, followed by 27°C for 20 days, then air curing
E8	75°C water curing for 7 days, followed by 27°C for 20 days, then air curing

Notes: (1) The air cured cubes were stored in a room where the temperature was maintained at 25 ± 5°C.
(2) The mean relative humidity of the room over the test period was about 80%.

Table 6 - Example of Allocation of Cubes

Curing Environment	Test Age					
	7 Days	28 Days	56 Days	90 Days	180 Days	360 Days
E1	1 2 3	1 4 6	1 4 6	1 4 6	1 4 6	1 4 6
	- - -	10 11 12	- - -	- - -	- - -	- - -
E2	- - -	2 4 5	2 4 5	2 4 5	2 4 5	2 4 5
E3	- - -	3 5 6	3 5 6	3 5 6	3 5 6	3 5 6
E4	- - -	9 11 12	9 11 12	9 11 12	9 11 12	9 11 12
E5	- - -	7 8 9	7 8 9	7 8 9	7 8 9	7 8 9
E6	- - -	8 10 11	8 10 11	8 10 11	8 10 11	8 10 11
E7	- - -	7 10 12	7 10 12	7 10 12	7 10 12	7 10 12
E8	- - -	1 2 3	1 2 3	1 2 3	1 2 3	1 2 3

Notes : (1) 1 to 12 are batch numbers.
(2) The example shown is for mix M8 : Grade 45 with 45% PFA replacement.

Table 7 - Density and Compressive Strength of Concrete Mix M1 under Various Curing Environments

Curing Environment	Age at Test											
	7 Days			28 Days			56 Days			90 Days		
	Density (kg/m³)	Compressive Strength (MPa)	Mean Strength (MPa)	Density (kg/m³)	Compressive Strength (MPa)	Mean Strength (MPa)	Density (kg/m³)	Compressive Strength (MPa)	Mean Strength (MPa)	Density (kg/m³)	Compressive Strength (MPa)	Mean Strength (MPa)
	2380	26.0		2400	38.5		2380	44.0		2370	43.5	
	2380	26.0		2400	39.5		2360	42.5		2360	42.5	
E1	2370	26.0	26.0	2380	39.0	39.0	2370	42.0	42.8	2370	42.5	42.8
	--	--		2400	39.0		--	--		--	--	
	--	--		2390	38.5		--	--		--	--	
	--	--		2410	39.5		--	--		--	--	
	--	--		2390	36.0		2370	43.0		2360	39.5	
E2	--	--	--	2390	37.5	37.0	2370	42.5	43.0	2370	42.5	41.2
	--	--		2400	37.5		2370	43.5		2380	41.5	
	--	--		2400	38.0		2370	42.0		2360	43.5	
E3	--	--	--	2380	37.5	37.5	2370	42.0	42.0	2360	43.0	43.5
	--	--		2400	37.0		2370	42.0		2350	44.0	
	--	--		2370	30.0		2380	30.5		2390	30.0	
E4	--	--	--	2370	29.5	28.7	2360	31.0	30.2	2380	28.5	28.5
	--	--		2380	26.5		2370	29.0		2370	27.0	
	--	--		2360	32.5		2350	34.5		2380	36.0	
E5	--	--	--	2360	34.5	33.5	2360	36.5	35.5	2370	35.5	35.3
	--	--		2370	33.5		2370	35.5		2370	34.5	
	--	--		2400	36.5		2360	38.0		2360	40.5	
E6	--	--	--	2410	36.0	36.0	2360	38.5	38.0	2350	37.0	38.0
	--	--		2380	35.5		2360	37.5		2350	36.5	
	--	--		2410	37.0		2370	41.5		2360	41.0	
E7	--	--	--	2390	37.0	37.5	2350	42.5	42.3	2360	44.5	42.0
	--	--		2380	38.5		2360	43.0		2350	40.5	
	--	--		2410	34.0		2350	36.0		2380	35.0	
E8	--	--	--	2390	33.0	33.0	2340	34.5	35.8	2355	34.5	34.5
	--	--		2400	32.0		2360	37.0		2365	34.0	

Table 8 - Density and Compressive Strength of Concrete Mix M2 under Various Curing Environments

Curing Environment	Age at Test											
	7 Days			28 Days			56 Days			90 Days		
	Density (kg/m³)	Compressive Strength (MPa)	Mean Strength (MPa)	Density (kg/m³)	Compressive Strength (MPa)	Mean Strength (MPa)	Density (kg/m³)	Compressive Strength (MPa)	Mean Strength (MPa)	Density (kg/m³)	Compressive Strength (MPa)	Mean Strength (MPa)
	2390	38.5		2390	50.5		2380	60.5		2380	57.5	
	2400	40.5		2400	51.5		2360	60.5		2390	58.5	
E1	2380	39.5	39.5	2410	53.5	52.3	2360	60.5	60.5	2360	58.5	58.2
	--	--		2380	53.5		--	--		--	--	
	--	--		2380	53.5		--	--		--	--	
	--	--		2380	51.5		--	--		--	--	
	--	--		2370	49.5		2380	58.0		2360	54.0	
E2	--	--	--	2390	52.0	50.8	2350	57.0	57.2	2360	56.0	55.5
	--	--		2380	51.0		2360	56.5		2360	56.5	
	--	--		2390	52.5		2360	55.5		2360	58.5	
E3	--	--	--	2380	51.5	52.0	2370	59.0	57.8	2360	56.5	57.7
	--	--		2380	52.0		2370	59.0		2360	58.0	
	--	--		2370	40.0		2370	42.0		2380	40.0	
E4	--	--	--	2360	39.5	39.2	2370	44.0	43.8	2370	39.5	39.8
	--	--		2380	38.0		2380	44.0		2380	40.0	
	--	--		2360	52.0		2360	49.0		2360	49.0	
E5	--	--	--	2370	49.5	50.2	2370	52.5	50.2	2360	48.5	50.3
	--	--		2370	49.0		2350	49.0		2370	53.5	
	--	--		2370	53.0		2370	56.0		2360	56.0	
E6	--	--	--	2380	54.0	53.2	2360	54.0	54.2	2360	56.5	54.8
	--	--		2360	52.5		2350	52.5		2360	52.0	
	--	--		2400	47.5		2370	53.0		2370	53.5	
E7	--	--	--	2400	48.0	47.5	2370	52.5	53.0	2360	54.0	53.7
	--	--		2390	47.0		2370	53.5		2360	53.5	
	--	--		2380	40.5		2350	46.0		2365	42.5	
E8	--	--	--	2390	42.0	41.3	2340	45.0	45.5	2370	43.5	43.3
	--	--		2390	41.5		2350	45.5		2355	44.0	

Table 9 - Density and Compressive Strength of Concrete Mix M3 under Various Curing Environments

Curing Environment	Age at Test											
	7 Days			28 Days			56 Days			90 Days		
	Density (kg/m^3)	Compressive Strength (MPa)	Mean Strength (MPa)	Density (kg/m^3)	Compressive Strength (MPa)	Mean Strength (MPa)	Density (kg/m^3)	Compressive Strength (MPa)	Mean Strength (MPa)	Density (kg/m^3)	Compressive Strength (MPa)	Mean Strength (MPa)
E1	2400 2390 2380 -- -- --	25.0 25.0 23.5 -- -- --	24.5	2390 2390 2380 2405 2385 2385	38.5 40.0 41.5 40.5 40.0 38.0	39.8	2390 2375 2380 -- -- --	46.5 47.0 46.5 -- -- --	46.7	2380 2370 2370 -- -- --	50.0 50.0 48.5 -- -- --	49.5
E2	-- -- --	-- -- --	--	2390 2400 2390	36.0 36.5 35.0	35.8	2375 2365 2370	43.5 45.0 42.5	43.7	2380 2370 2370	46.5 47.5 46.0	46.7
E3	-- -- --	-- -- --	--	2400 2400 2390	35.0 36.0 39.0	36.7	2385 2380 2375	44.5 43.0 44.0	43.8	2360 2380 2360	44.5 46.0 47.0	45.8
E4	-- -- --	-- -- --	--	2380 2385 2375	29.5 30.0 29.0	29.5	2380 2390 2375	32.5 34.0 32.0	32.8	2380 2390 2380	32.5 33.5 33.5	33.2
E5	-- -- --	-- -- --	--	2380 2370 2380	34.5 35.5 36.5	35.5	2380 2365 2365	38.0 40.0 39.5	39.2	2370 2360 2370	37.0 40.5 39.5	39.0
E6	-- -- --	-- -- --	--	2360 2375 2365	38.0 41.0 38.5	39.2	2370 2370 2370	41.5 43.0 40.0	41.5	2370 2360 2380	43.0 47.5 41.0	43.8
E7	-- -- --	-- -- --	--	2400 2380 2380	46.0 49.5 45.0	46.8	2390 2380 2375	46.5 50.5 47.5	48.2	2400 2380 2380	51.5 53.0 49.5	51.3
E8	-- -- --	-- -- --	--	2400 2390 2390	39.5 38.5 38.5	38.8	2385 2375 2380	42.0 41.5 41.0	41.5	2380 2360 2380	43.0 43.0 42.5	42.8

Table 10 - Density and Compressive Strength of Concrete Mix M4 under Various Curing Environments

Curing Environment	Age at Test											
	7 Days			28 Days			56 Days			90 Days		
	Density (kg/m³)	Compressive Strength (MPa)	Mean Strength (MPa)	Density (kg/m³)	Compressive Strength (MPa)	Mean Strength (MPa)	Density (kg/m³)	Compressive Strength (MPa)	Mean Strength (MPa)	Density (kg/m³)	Compressive Strength (MPa)	Mean Strength (MPa)
E1	2400	40.5	39.7	2400	60.0	58.0	2390	68.0	67.2	2390	68.0	68.0
	2390	39.5		2405	59.0		2390	67.5		2370	69.0	
	2390	39.0		2395	58.0		2390	66.0		2390	67.0	
	--	--		2405	57.5		--	--		--	--	
	--	--		2395	57.5		--	--		--	--	
	--	--		2400	56.0		--	--		--	--	
E2	--	--	--	2405	54.5	54.7	2395	62.0	62.5	2390	69.5	68.2
	--	--		2400	56.0		2390	63.5		2380	68.0	
	--	--		2405	53.5		2395	62.0		2380	67.0	
E3	--	--	--	2405	54.0	53.7	2400	62.5	62.2	2390	68.5	67.3
	--	--		2400	53.0		2390	62.0		2390	67.0	
	--	--		2405	54.0		2385	62.0		2390	66.5	
E4	--	--	--	2390	45.5	45.3	2380	48.0	48.2	2385	50.5	49.5
	--	--		2380	46.0		2390	48.0		2380	48.5	
	--	--		2385	44.5		2380	48.5		2385	49.5	
E5	--	--	--	2390	53.5	54.5	2390	56.5	56.5	2390	60.0	60.0
	--	--		2380	54.0		2395	57.0		2390	60.0	
	--	--		2380	56.0		2390	56.0		2390	60.0	
E6	--	--	--	2395	57.0	55.5	2380	59.0	58.7	2380	61.5	60.8
	--	--		2390	54.0		2380	58.0		2385	60.5	
	--	--		2380	55.5		2380	59.0		2380	60.5	
E7	--	--	--	2410	64.5	63.0	2400	66.5	65.7	2390	68.0	67.8
	--	--		2395	64.0		2400	66.5		2385	68.0	
	--	--		2395	60.5		2390	64.0		2390	67.5	
E8	--	--	--	2400	55.5	57.3	2390	57.5	58.8	2390	60.0	60.5
	--	--		2395	59.0		2395	59.0		2380	62.0	
	--	--		2395	57.5		2400	60.0		2390	59.5	

Table 11 - Density and Compressive Strength of Concrete Mix M5 under Various Curing Environments

Curing Environment	Age at Test: 7 Days Density (kg/m³)	7 Days Compressive Strength (MPa)	7 Days Mean Strength (MPa)	28 Days Density (kg/m³)	28 Days Compressive Strength (MPa)	28 Days Mean Strength (MPa)	56 Days Density (kg/m³)	56 Days Compressive Strength (MPa)	56 Days Mean Strength (MPa)	90 Days Density (kg/m³)	90 Days Compressive Strength (MPa)	90 Days Mean Strength (MPa)
	2370	21.5		2370	38.5		2330	44.5		2350	49.5	
	2380	22.5		2360	38.5		2350	48.5		2340	49.5	
E1	2370	22.0	22.0	2360	40.0	38.7	2350	50.0	47.7	2350	48.5	49.2
	--	--		2390	37.5		--	--		--	--	
	--	--		2370	38.5		--	--		--	--	
	--	--		2380	39.0		--	--		--	--	
	--	--		2370	33.0		2340	40.0		2340	43.5	
E2	--	--	--	2360	32.5	32.5	2350	40.5	40.7	2350	45.0	44.3
	--	--		2380	32.0		2350	41.5		2350	44.5	
	--	--		2360	34.0		2350	40.5		2330	43.5	
E3	--	--	--	2360	32.5	32.8	2340	41.0	40.7	2340	45.0	44.2
	--	--		2370	32.0		2340	40.5		2340	44.0	
	--	--		2360	28.0		2370	29.5		2370	28.5	
E4	--	--	--	2350	29.5	28.0	2360	31.5	29.7	2370	28.5	28.5
	--	--		2350	26.5		2370	28.0		2370	28.5	
	--	--		2340	31.5		2340	35.0		2330	35.0	
E5	--	--	--	2330	30.5	31.2	2340	35.5	34.5	2340	38.0	36.0
	--	--		2350	31.5		2340	33.0		2350	35.0	
	--	--		2340	34.0		2340	37.5		2340	41.0	
E6	--	--	--	2350	33.0	33.5	2340	37.0	36.5	2350	41.5	40.3
	--	--		2350	33.5		2340	35.0		2330	38.5	
	--	--		2370	45.5		2380	45.5		2360	49.0	
E7	--	--	--	2380	43.5	43.5	2370	48.0	46.2	2360	48.0	47.8
	--	--		2380	41.5		2360	45.0		2360	46.5	
	--	--		2370	41.0		2380	41.5		2370	43.0	
E8	--	--	--	2400	40.0	41.2	2380	42.5	42.3	2385	43.0	43.0
	--	--		2380	42.5		2380	43.0		2370	43.0	

Table 12 - Density and Compressive Strength of Concrete Mix M6 under Various Curing Environments

Curing Environment	Age at Test											
	7 Days			28 Days			56 Days			90 Days		
	Density (kg/m³)	Compressive Strength (MPa)	Mean Strength (MPa)	Density (kg/m³)	Compressive Strength (MPa)	Mean Strength (MPa)	Density (kg/m³)	Compressive Strength (MPa)	Mean Strength (MPa)	Density (kg/m³)	Compressive Strength (MPa)	Mean Strength (MPa)
	2370	32.5		2370	50.0		2350	56.5		2350	60.5	
	2370	31.5		2380	51.5		2360	61.5		2370	65.5	
E1	2380	32.0	32.0	2370	51.0	51.5	2350	62.5	60.2	2360	63.5	63.2
	--	--		2390	52.5		--	--		--	--	
	--	--		2390	52.0		--	--		--	--	
	--	--		2390	52.0		--	--		--	--	
	--	--		2380	46.0		2360	54.5		2360	58.0	
E2	--	--	--	2380	44.5	45.8	2350	57.5	57.0	2360	62.0	60.5
	--	--		2360	47.0		2350	59.0		2370	61.5	
	--	--		2380	47.5		2360	59.0		2370	63.5	
E3	--	--	--	2390	46.5	47.3	2360	59.0	58.3	2360	61.0	62.3
	--	--		2380	48.0		2340	57.0		2360	62.5	
	--	--		2370	41.5		2360	39.0		2370	44.0	
E4	--	--	--	2360	39.5	39.8	2370	37.5	39.0	2380	40.0	43.3
	--	--		2350	38.5		2370	40.5		2370	46.0	
	--	--		2360	43.0		2340	48.0		2350	52.0	
E5	--	--	--	2350	44.0	43.3	2350	46.5	46.7	2340	51.0	50.2
	--	--		2350	43.0		2350	45.5		2340	47.5	
	--	--		2350	46.0		2360	47.5		2350	50.5	
E6	--	--	--	2360	47.0	45.7	2350	46.5	47.5	2360	51.0	50.8
	--	--		2340	44.0		2340	48.5		2350	51.0	
	--	--		2380	57.0		2370	62.0		2370	63.0	
E7	--	--	--	2390	55.0	56.3	2390	61.5	61.5	2390	61.0	62.8
	--	--		2390	57.0		2390	61.0		2380	64.5	
	--	--		2390	56.5		2380	59.0		2390	58.5	
E8	--	--	--	2400	55.0	55.5	2380	58.5	58.0	2380	57.5	58.3
	--	--		2390	55.0		2380	56.5		2375	59.0	

Table 13 - Density and Compressive Strength of Concrete Mix M7 under Various Curing Environments

Curing Environment	Age at Test											
	7 Days			28 Days			56 Days			90 Days		
	Density (kg/m³)	Compressive Strength (MPa)	Mean Strength (MPa)	Density (kg/m³)	Compressive Strength (MPa)	Mean Strength (MPa)	Density (kg/m³)	Compressive Strength (MPa)	Mean Strength (MPa)	Density (kg/m³)	Compressive Strength (MPa)	Mean Strength (MPa)
	2380	21.5		2390	41.0		2380	49.5		2380	51.5	
	2380	23.0		2380	44.5		2375	53.5		2375	53.0	
E1	2370	22.5	22.3	2390	40.5	41.2	2365	50.5	51.2	2370	51.5	52.0
	--	--		2390	40.0		--	--		--	--	
	--	--		2390	40.0		--	--		--	--	
	--	--		2380	41.0		--	--		--	--	
	--	--		2390	31.5		2360	45.5		2355	47.0	
E2	--	--	--	2390	32.0	31.8	2360	45.5	45.0	2360	46.5	46.5
	--	--		2390	32.0		2370	44.0		2370	46.0	
	--	--		2380	31.0		2375	48.0		2365	47.0	
E3	--	--	--	2390	31.0	31.3	2380	45.5	46.2	2380	47.0	47.5
	--	--		2380	32.0		2365	45.0		2365	48.5	
	--	--		2360	28.5		2370	36.0		2380	31.0	
E4	--	--	--	2360	26.5	27.0	2370	32.5	32.8	2380	31.0	30.8
	--	--		2360	26.0		2360	30.0		2370	30.5	
	--	--		2350	33.0		2360	38.0		2370	40.0	
E5	--	--	--	2350	33.0	33.2	2365	39.5	38.2	2360	39.5	39.5
	--	--		2350	33.5		2360	37.0		2360	39.0	
	--	--		2360	35.5		2355	40.5		2370	44.0	
E6	--	--	--	2350	38.5	36.0	2360	46.0	41.7	2360	45.0	43.2
	--	--		2350	34.0		2365	38.5		2370	40.5	
	--	--		2390	50.5		2385	52.5		2380	52.5	
E7	--	--	--	2390	52.5	50.0	2385	55.0	54.3	2380	56.5	53.8
	--	--		2380	47.0		2375	55.5		2370	52.5	
	--	--		2390	40.5		2375	42.5		2375	43.5	
E8	--	--	--	2380	42.0	41.5	2375	43.0	43.2	2375	42.5	43.3
	--	--		2370	42.0		2380	44.0		2375	44.0	

Table 14 - Density and Compressive Strength of Concrete Mix M8 under Various Curing Environments

Curing Environment	Age at Test											
	7 Days			28 Days			56 Days			90 Days		
	Density (kg/m³)	Compressive Strength (MPa)	Mean Strength (MPa)	Density (kg/m³)	Compressive Strength (MPa)	Mean Strength (MPa)	Density (kg/m³)	Compressive Strength (MPa)	Mean Strength (MPa)	Density (kg/m³)	Compressive Strength (MPa)	Mean Strength (MPa)
	2380	32.5		2390	54.5		2380	64.0		2380	69.5	
	2380	33.5		2380	54.0		2375	63.0		2380	70.5	
E1	2380	31.5	32.5	2380	55.5	55.0	2370	63.5	63.5	2370	69.5	69.8
	--	--		2400	59.5		--	--		--	--	
	--	--		2390	53.0		--	--		--	--	
	--	--		2390	53.5		--	--		--	--	
	--	--		2370	44.5		2365	61.0		2370	65.5	
E2	--	--	--	2380	42.5	43.5	2375	58.5	59.2	2370	63.0	64.0
	--	--		2390	43.5		2365	58.0		2360	63.5	
	--	--		2380	45.5		2370	58.0		2370	66.5	
E3	--	--	--	2390	43.0	44.3	2365	59.0	58.2	2370	64.5	65.2
	--	--		2380	44.5		2365	57.5		2360	64.5	
	--	--		2370	36.5		2370	39.5		2380	43.0	
E4	--	--	--	2370	34.0	35.0	2375	37.5	38.3	2380	40.0	41.5
	--	--		2370	34.5		2375	38.0		2380	41.5	
	--	--		2360	45.5		2370	51.5		2360	53.0	
E5	--	--	--	2360	46.0	45.3	2375	52.5	51.5	2360	56.0	54.5
	--	--		2360	44.5		2365	50.5		2360	54.5	
	--	--		2360	47.5		2360	54.5		2360	58.0	
E6	--	--	--	2370	52.0	48.5	2370	58.5	54.8	2370	62.0	58.2
	--	--		2370	46.0		2370	51.5		2360	54.5	
	--	--		2380	63.0		2370	65.0		2370	67.5	
E7	--	--	--	2380	65.5	62.5	2385	70.0	65.3	2380	69.5	67.2
	--	--		2380	59.0		2380	61.0		2370	64.5	
	--	--		2390	56.0		2375	55.5		2370	58.5	
E8	--	--	--	2370	55.0	56.0	2370	57.0	56.7	2370	56.0	57.5
	--	--		2380	57.0		2380	57.5		2370	58.0	

Table 15 - Density and Compressive Strength of Concrete Mix M9 under Various Curing Environments

Curing Environment	Age at Test											
	7 Days			28 Days			56 Days			90 Days		
	Density (kg/m³)	Compressive Strength (MPa)	Mean Strength (MPa)	Density (kg/m³)	Compressive Strength (MPa)	Mean Strength (MPa)	Density (kg/m³)	Compressive Strength (MPa)	Mean Strength (MPa)	Density (kg/m³)	Compressive Strength (MPa)	Mean Strength (MPa)
E1	2370 2360 2360 -- -- --	22.5 22.5 22.5 -- -- --	22.5	2350 2370 2370 2370 2360 2360	40.5 44.0 42.0 43.5 43.5 44.0	42.9	2340 2350 2350 -- -- --	46.5 51.0 51.0 -- -- --	49.5	2350 2350 2345 -- -- --	52.5 56.0 54.5 -- -- --	54.3
E2	-- -- --	-- -- --	--	2380 2370 2370	32.5 30.0 30.5	31.0	2350 2340 2350	45.0 44.5 43.5	44.3	2350 2345 2350	50.0 50.5 50.5	50.3
E3	-- -- --	-- -- --	--	2370 2370 2360	29.5 30.0 28.5	29.3	2350 2350 2330	40.0 42.5 39.5	40.7	2350 2340 2345	47.0 48.5 46.0	47.2
E4	-- -- --	-- -- --	--	2340 2330 2330	30.5 31.0 29.0	30.2	2340 2340 2340	35.0 33.0 32.0	33.3	2355 2355 2360	37.0 34.5 35.5	35.7
E5	-- -- --	-- -- --	--	2320 2340 2320	36.0 36.0 34.5	35.5	2340 2340 2330	37.0 39.0 40.0	38.7	2345 2350 2350	45.0 43.0 44.5	44.2
E6	-- -- --	-- -- --	--	2330 2330 2330	37.5 38.0 35.5	37.0	2340 2340 2350	41.5 40.5 39.5	40.5	2350 2350 2355	45.5 43.5 45.0	44.7
E7	-- -- --	-- -- --	--	2370 2370 2370	52.0 51.0 51.5	51.5	2360 2370 2350	52.5 52.0 50.5	51.7	2335 2355 2350	54.0 54.5 55.0	54.5
E8	-- -- --	-- -- --	--	2370 2370 2360	48.0 47.5 49.0	48.2	2350 2340 2360	47.0 47.0 49.0	47.7	2355 2355 2355	48.5 49.5 50.5	49.5

Table 16 - Density and Compressive Strength of Concrete Mix M10 under Various Curing Environments

Curing Environment	Age at Test											
	7 Days			28 Days			56 Days			90 Days		
	Density (kg/m³)	Compressive Strength (MPa)	Mean Strength (MPa)	Density (kg/m³)	Compressive Strength (MPa)	Mean Strength (MPa)	Density (kg/m³)	Compressive Strength (MPa)	Mean Strength (MPa)	Density (kg/m³)	Compressive Strength (MPa)	Mean Strength (MPa)
	2360	30.0		2360	53.5		2350	64.5		2350	64.5	
	2360	30.0		2350	52.5		2350	60.9		2340	66.4	
E1	2360	30.5	30.2	2360	54.5	54.8	2350	64.4	63.3	2340	69.4	66.8
	--	--		2360	56.5		--	--		--	--	
	--	--		2360	56.5		--	--		--	--	
	--	--		2360	55.5		--	--		--	--	
	--	--		2350	44.0		2340	56.3		2365	61.0	
E2	--	--	--	2370	41.5	42.2	2340	53.5	54.1	2335	58.5	59.8
	--	--		2350	41.0		2350	52.5		2340	60.0	
	--	--		2350	40.0		2340	52.5		2345	60.0	
E3	--	--	--	2370	42.0	40.8	2340	56.0	54.7	2355	61.0	60.2
	--	--		2350	40.5		2350	55.5		2355	59.5	
	--	--		2320	35.5		2340	41.5		2335	44.0	
E4	--	--	--	2320	36.5	35.3	2330	41.0	39.5	2340	45.5	42.2
	--	--		2330	34.0		2350	36.0		2350	37.0	
	--	--		2320	44.5		2340	48.0		2335	52.0	
E5	--	--	--	2330	49.0	46.8	2340	52.0	48.7	2330	56.0	54.0
	--	--		2310	47.0		2340	46.0		2330	54.0	
	--	--		2330	45.5		2340	51.5		2340	54.5	
E6	--	--	--	2320	49.0	47.5	2340	52.0	51.5	2345	57.5	56.0
	--	--		2330	48.0		2330	51.0		2335	56.0	
	--	--		2370	59.0		2360	61.0		2360	63.0	
E7	--	--	--	2360	61.0	61.0	2350	63.0	62.8	2345	65.0	63.0
	--	--		2360	63.0		2350	64.5		2355	61.0	
	--	--		2350	55.0		2340	58.5		2335	60.5	
E8	--	--	--	2360	58.0	56.7	2340	57.0	57.8	2340	58.5	59.7
	--	--		2340	57.0		2350	58.0		2350	60.0	

Table 17 - Mean Compressive Strengths for Mixes M1 to M10

Curing Environment	Age (days)	Grade 30 Concrete					Grade 45 Concrete				
		M1	M3	M5	M7	M9	M2	M4	M6	M8	M10
E1	7	26.0	24.5	22.0	22.3	22.5	39.5	39.7	32.0	32.5	30.2
	28	39.0	39.8	38.7	41.2	42.9	52.3	58.0	51.5	55.0	54.8
	56	42.8	46.7	47.7	51.2	49.5	60.5	67.2	60.2	63.5	63.3
	90	42.8	49.5	49.2	52.0	54.3	58.2	68.0	63.2	69.8	66.8
E2	28	37.0	35.8	32.5	31.8	31.0	50.8	54.7	45.8	43.5	42.2
	56	43.0	43.7	40.7	45.0	44.3	57.2	62.5	57.0	59.2	54.1
	90	41.2	46.7	44.3	46.5	50.3	55.5	68.2	60.5	64.0	59.8
E3	28	37.5	36.7	32.8	31.3	29.3	52.0	53.7	47.3	44.3	40.8
	56	42.0	43.8	40.7	46.2	40.7	57.8	62.2	58.3	58.2	54.7
	90	43.5	45.8	44.2	47.5	47.2	57.7	67.3	62.3	65.2	60.2
E4	28	28.7	29.5	28.0	27.0	30.2	39.2	45.3	39.8	35.0	35.3
	56	30.2	32.8	29.7	32.8	33.3	43.3	48.2	39.0	38.3	39.5
	90	28.5	33.2	28.5	30.8	35.7	39.8	49.5	43.3	41.5	42.2
E5	28	33.5	35.5	31.2	33.2	35.5	50.2	54.5	43.3	45.3	46.8
	56	35.5	39.2	34.5	38.2	38.7	50.2	56.5	46.7	51.5	48.7
	90	35.3	39.0	36.0	39.5	44.2	50.3	60.0	50.2	54.5	54.0
E6	28	36.0	39.2	33.5	36.0	37.0	53.2	55.5	45.7	48.5	47.5
	56	38.0	41.5	36.5	41.7	40.5	54.2	58.7	47.5	54.8	51.5
	90	38.0	43.8	40.3	43.2	44.7	54.8	60.8	50.8	58.2	56.0
E7	28	37.5	46.8	43.5	50.0	51.5	47.5	63.0	56.3	62.5	61.0
	56	42.3	48.2	46.2	54.3	51.7	53.0	65.7	61.5	65.3	62.8
	90	42.0	51.3	47.8	53.8	54.5	53.7	67.8	62.8	67.2	63.0
E8	28	33.0	38.8	41.2	41.5	48.2	41.3	57.3	55.5	56.0	56.7
	56	35.8	41.5	42.3	43.2	47.7	45.5	58.8	58.0	56.7	57.8
	90	34.5	42.8	43.0	43.3	49.5	43.3	60.5	58.3	57.5	59.7

Notes : (1) The details of the concrete mixes M1 to M10 and the curing environments are given in Tables 4 and 5 respectively.
(2) The mean compressive strengths in this Table are taken from Tables 7 to 16 of this Report and are in units of MPa.

Table 18 - Normalisation Factors for Mixes M1 to M10

Concrete Mix	Grade 30 Concrete					Grade 45 Concrete				
	M1	M3	M5	M7	M9	M2	M4	M6	M8	M10
Normalisation Factor	0.974	0.955	0.982	0.922	0.886	1.013	0.914	1.029	0.964	0.967

Note : (1) The normalisation factors were calculated using equation (1).

Table 19 - Normalised Mean Compressive Strengths for Mixes M1 to M10

Curing Environment	Age (days)	Grade 30 Concrete					Grade 45 Concrete				
		M1	M3	M5	M7	M9	M2	M4	M6	M8	M10
E1	7	25.3	23.4	21.6	20.6	19.9	40.0	36.3	32.9	31.3	29.2
	28	38.0	38.0	38.0	38.0	38.0	53.0	53.0	53.0	53.0	53.0
	56	41.7	44.6	46.8	47.2	43.8	61.3	61.4	62.0	61.2	61.2
	90	41.7	47.3	48.3	48.0	48.1	58.9	62.1	65.0	67.3	64.6
E2	28	36.1	34.2	31.9	29.3	27.5	51.5	50.0	47.1	41.9	40.8
	56	41.9	41.7	40.0	41.5	39.2	58.0	57.1	58.7	57.0	52.3
	90	40.1	44.6	43.5	42.9	44.6	56.2	62.3	62.3	61.7	57.8
E3	28	36.5	35.0	32.2	28.9	26.0	52.7	49.1	48.7	42.7	39.5
	56	40.9	41.8	40.0	42.6	36.1	58.6	56.8	60.0	56.1	52.9
	90	42.4	43.7	43.4	43.8	41.8	58.5	61.5	64.1	62.8	58.2
E4	28	28.0	28.2	27.5	24.9	26.8	39.7	41.4	41.0	33.7	34.1
	56	29.4	31.3	29.2	30.3	29.5	43.9	44.0	40.1	36.9	38.2
	90	27.8	31.7	28.0	28.4	31.6	40.3	45.2	44.6	40.0	40.8
E5	28	32.6	33.9	30.6	30.6	31.4	50.9	49.8	44.6	43.7	45.3
	56	34.6	37.4	33.9	35.2	34.3	50.9	51.6	48.1	49.6	47.1
	90	34.4	37.2	35.3	36.4	39.1	51.0	54.8	51.7	52.5	52.2
E6	28	35.1	37.4	32.9	33.2	32.8	53.9	50.7	47.0	46.7	45.9
	56	37.0	39.6	35.8	38.5	35.9	54.9	53.6	48.9	52.8	49.8
	90	37.0	41.8	39.6	39.8	39.6	55.5	55.6	52.3	56.1	54.2
E7	28	36.5	44.7	42.7	46.1	45.6	48.1	57.6	57.9	60.2	59.0
	56	41.2	46.0	45.4	50.1	45.8	53.7	60.0	63.3	62.9	60.7
	90	40.9	49.0	46.9	49.6	48.3	54.4	62.0	64.6	64.8	60.9
E8	28	32.2	37.0	40.5	38.3	42.7	41.9	52.4	57.1	54.0	54.8
	56	34.9	39.6	41.5	39.8	42.3	46.1	53.7	59.7	54.6	55.9
	90	33.6	40.9	42.2	39.9	43.8	43.9	55.3	60.0	55.4	57.7

Notes : (1) The notes of Table 17 also apply to this Table.
(2) The normalised mean compressive strengths were calculated in accordance with Section 5.2.1.

Table 20 - Relative Strength Percentages for Mixes M1 to M10

Curing Environment	Age (days)	Relative Strength Percentage (%)									
		Grade 30 Concrete					Grade 45 Concrete				
		M1	M3	M5	M7	M9	M2	M4	M6	M8	M10
E1	7	67	62	57	54	52	76	68	62	59	55
	28	100	100	100	100	100	100	100	100	100	100
	56	110	117	123	124	115	116	116	117	115	116
	90	110	124	127	126	127	111	117	123	127	122
E2	28	95	90	84	77	72	97	94	89	79	77
	56	110	110	105	109	103	109	108	111	108	99
	90	106	117	114	113	117	106	118	117	116	109
E3	28	96	92	85	76	68	99	93	92	81	74
	56	108	110	105	112	95	111	107	113	106	100
	90	112	115	114	115	110	110	116	121	119	110
E4	28	74	74	72	66	70	75	78	77	64	64
	56	77	82	77	80	78	83	83	76	70	72
	90	73	83	74	75	83	76	85	84	75	77
E5	28	86	89	81	81	83	96	94	84	82	85
	56	91	98	89	93	90	96	97	91	94	89
	90	91	98	93	96	103	96	103	97	99	99
E6	28	92	98	87	87	86	102	96	89	88	87
	56	97	104	94	101	94	104	101	92	100	94
	90	97	110	104	105	104	105	105	99	106	102
E7	28	96	118	112	121	120	91	109	109	114	111
	56	108	121	119	132	121	101	113	119	119	115
	90	108	129	124	131	127	103	117	122	122	115
E8	28	85	97	106	101	112	79	99	108	102	103
	56	92	104	109	105	111	87	101	113	103	105
	90	88	108	111	105	115	83	104	113	105	109

Notes : (1) The details of the concrete mixes M1 to M10 and the curing environments are given in Tables 4 and 5 respectively.
(2) The relative strength percentages were calculated using equation (2).

LIST OF FIGURES

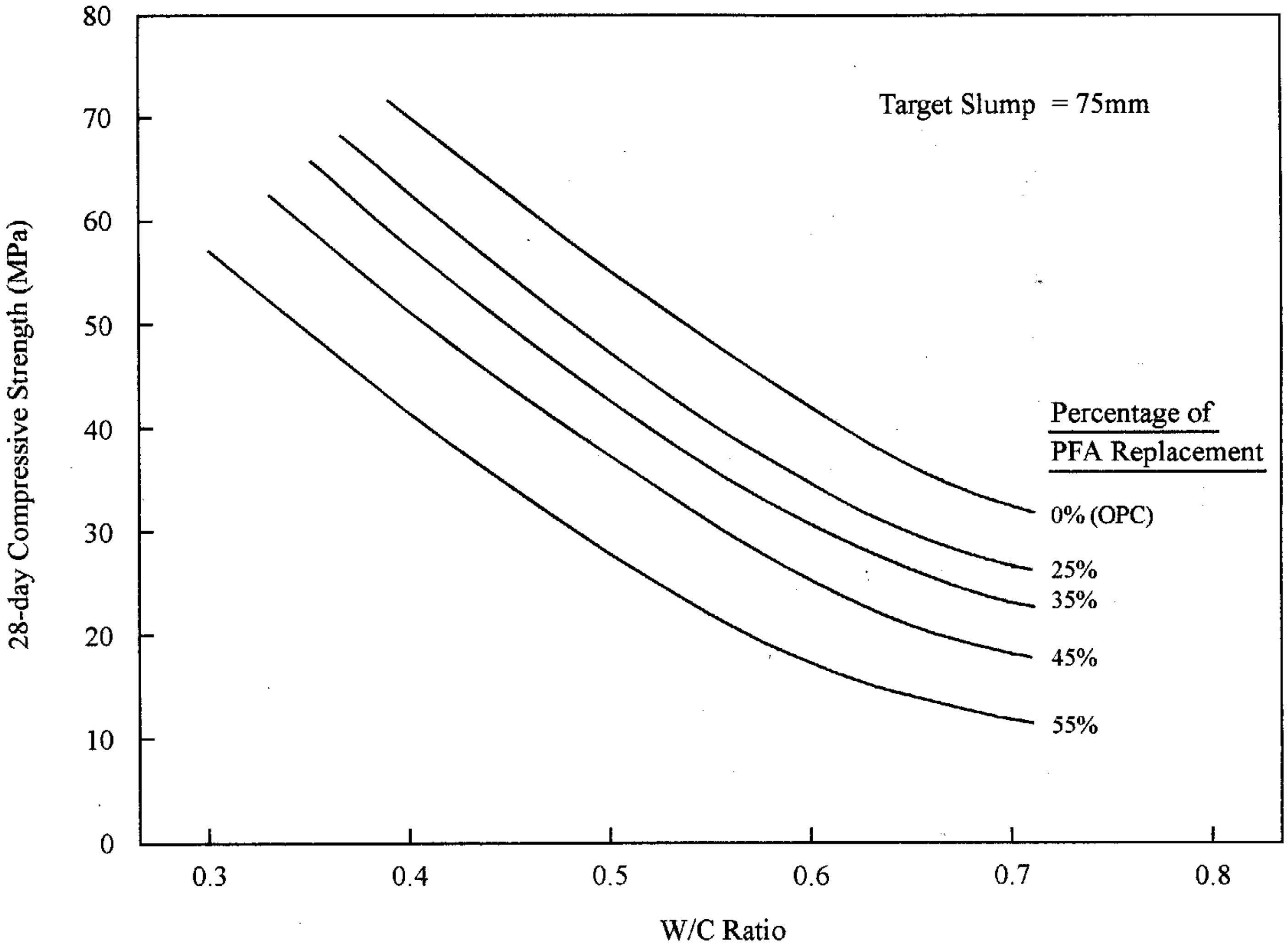

Figure 1 - Relationship between 28-day Compressive Strength and Water/Cement Ratio for OPC and PFA Concretes

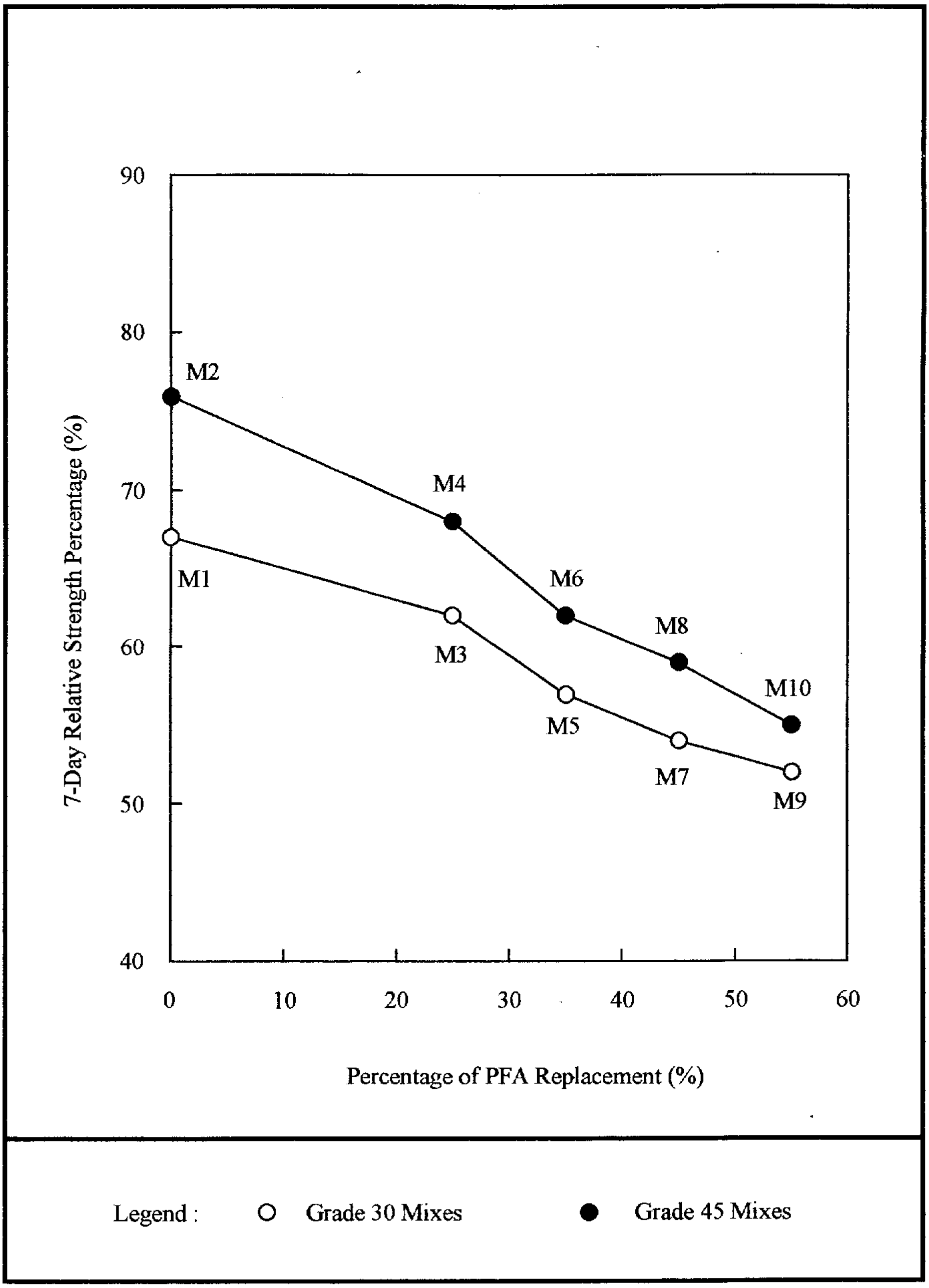

Figure 2 - 7-Day Relative Strength Percentage of OPC and PFA Concretes Cured under Environment E1

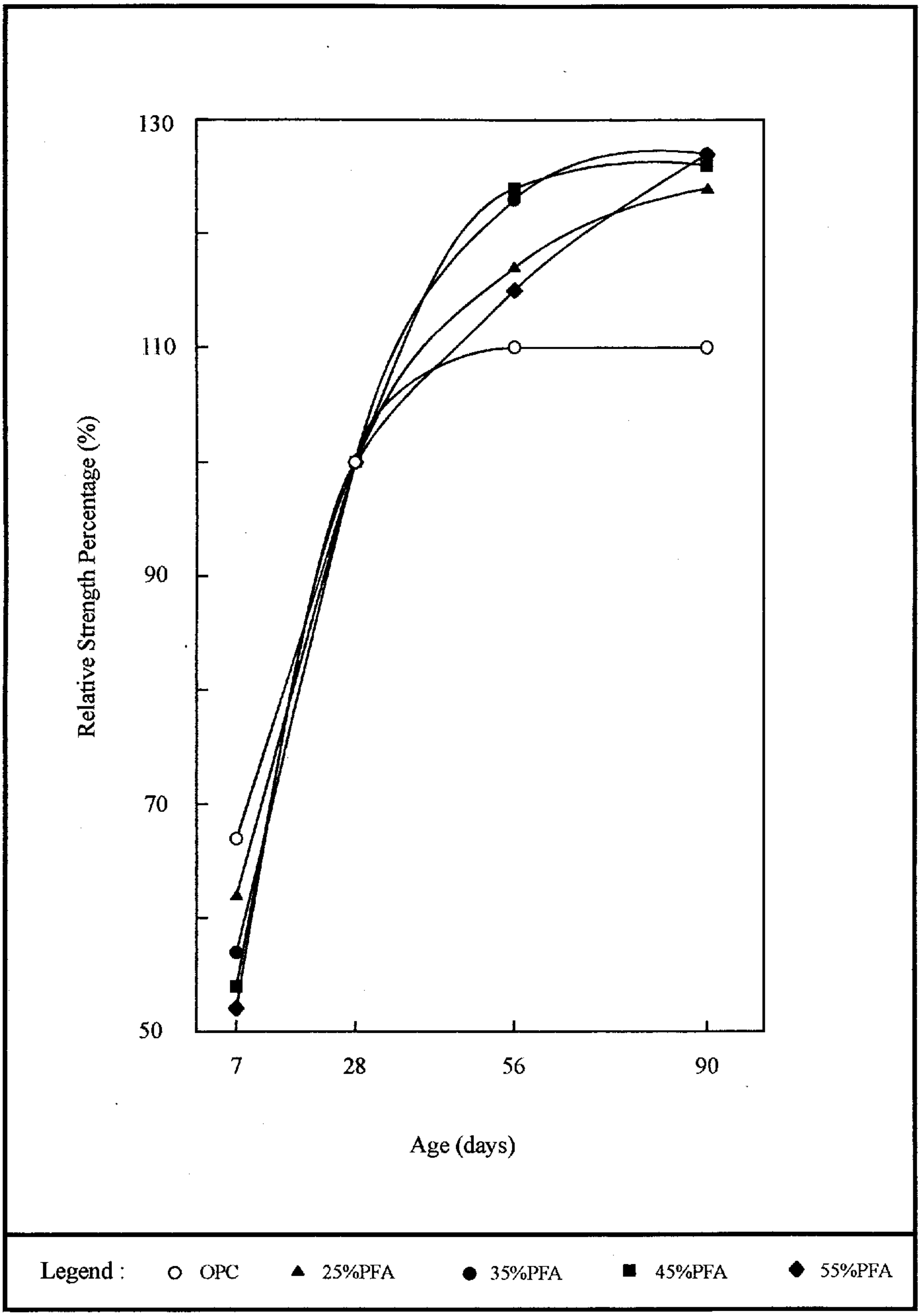

Figure 3 - Strength Development of Grade 30 OPC and PFA Concretes Cured under Environment E1

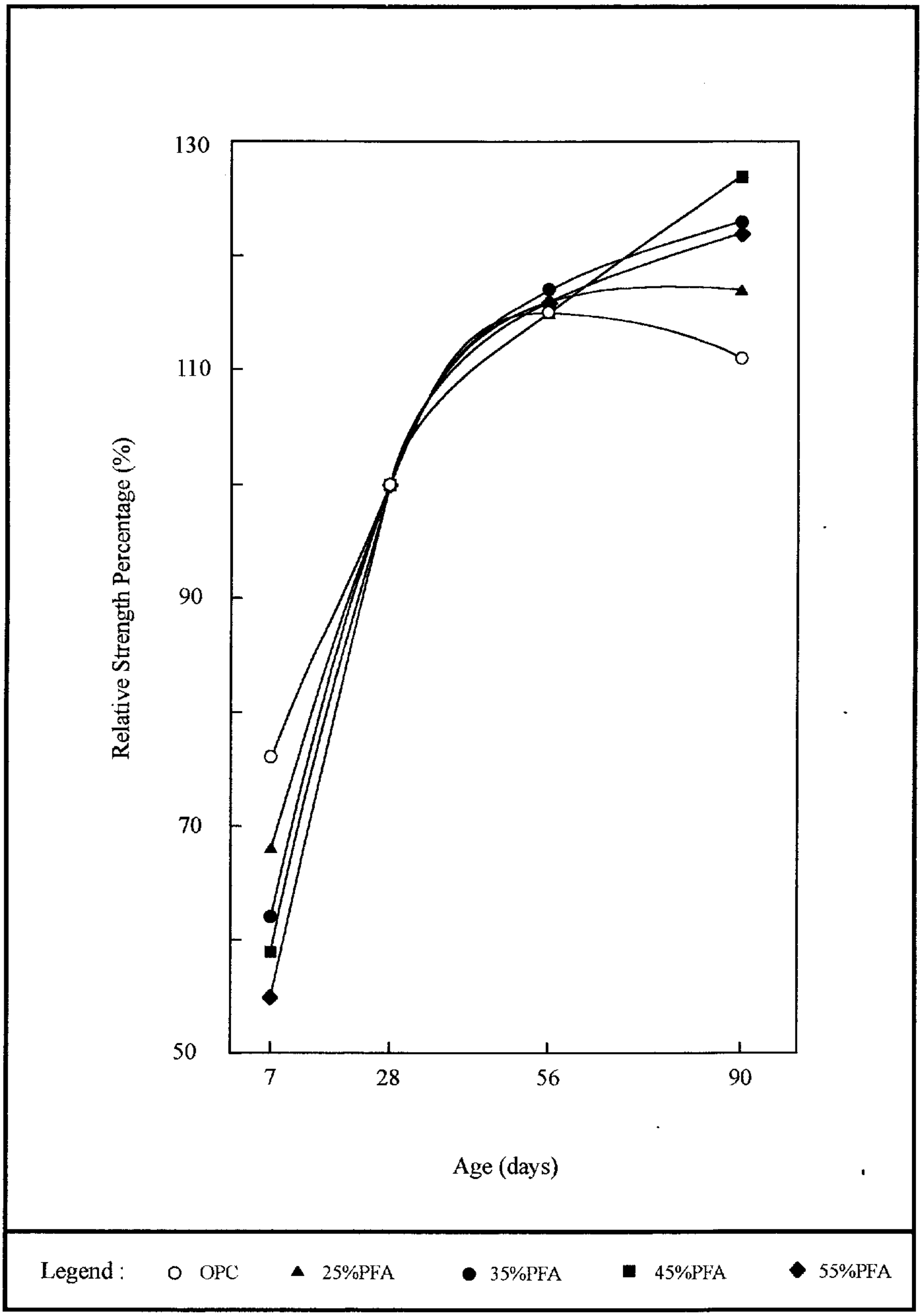

Figure 4 - Strength Development of Grade 45 OPC and PFA Concretes Cured under Environment E1

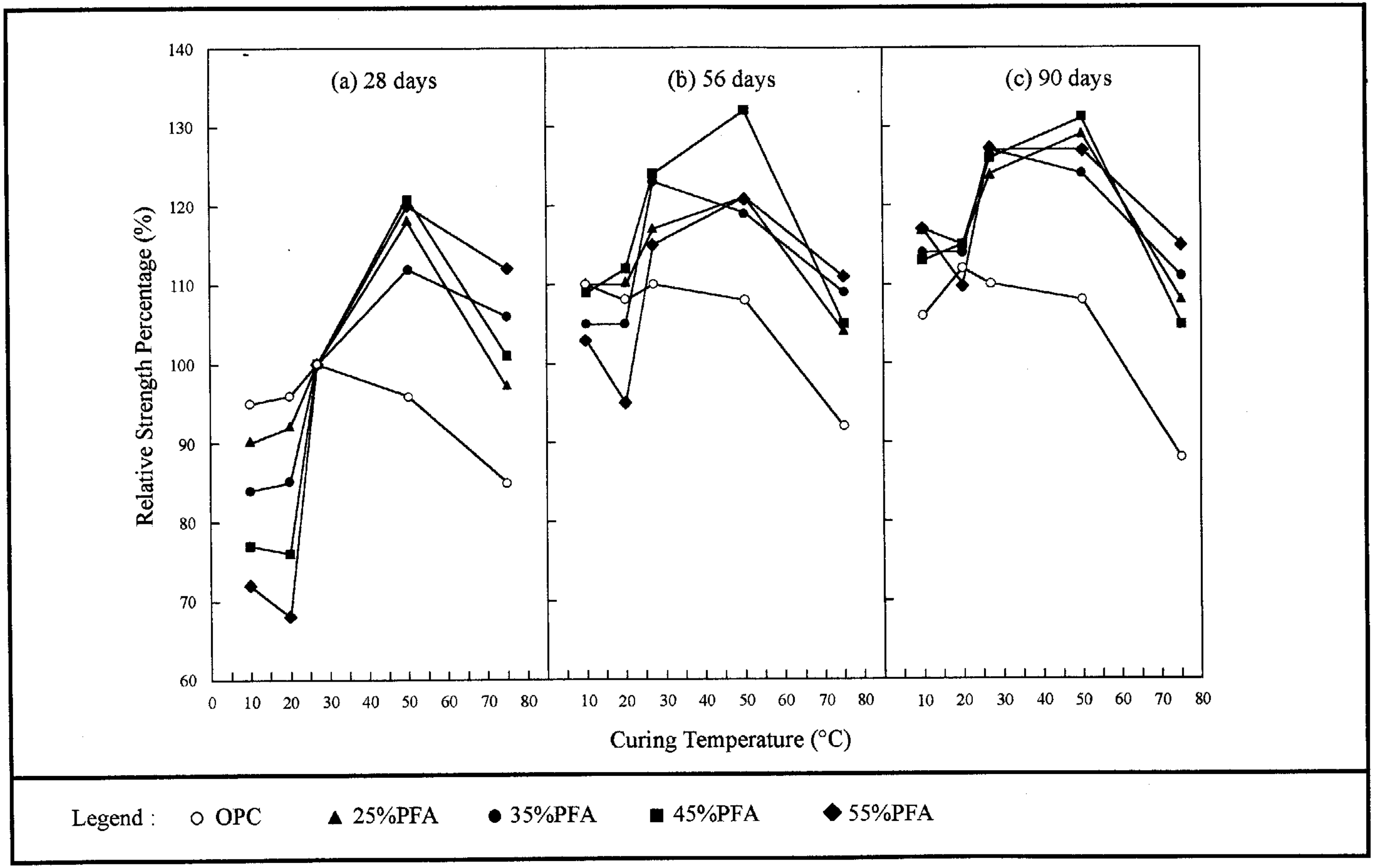

Figure 5 - Influence of Curing Temperature on the Strength Development of Grade 30 OPC and PFA Concretes

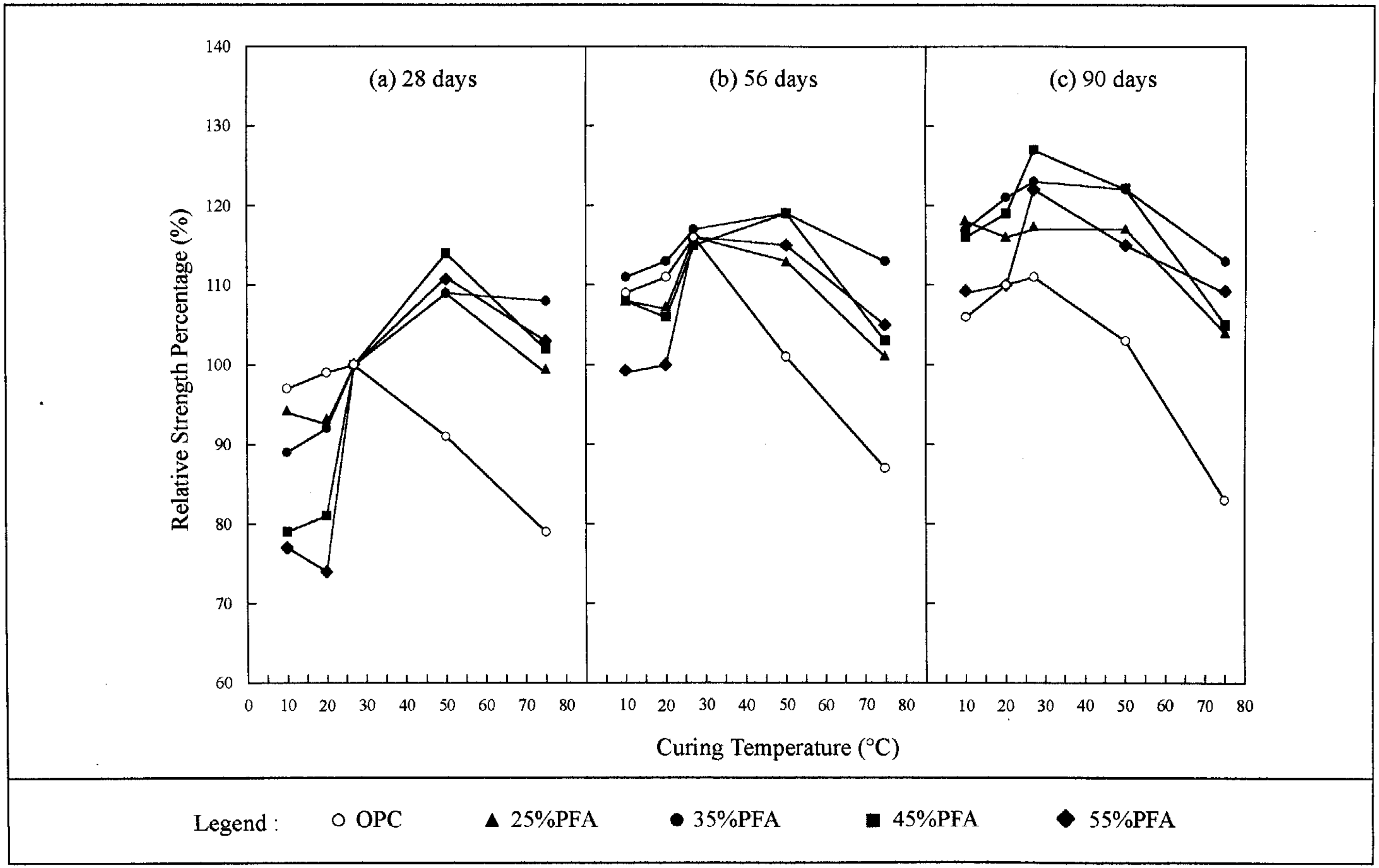

Figure 6 - Influence of Curing Temperature on the Strength Development of Grade 45 OPC and PFA Concretes

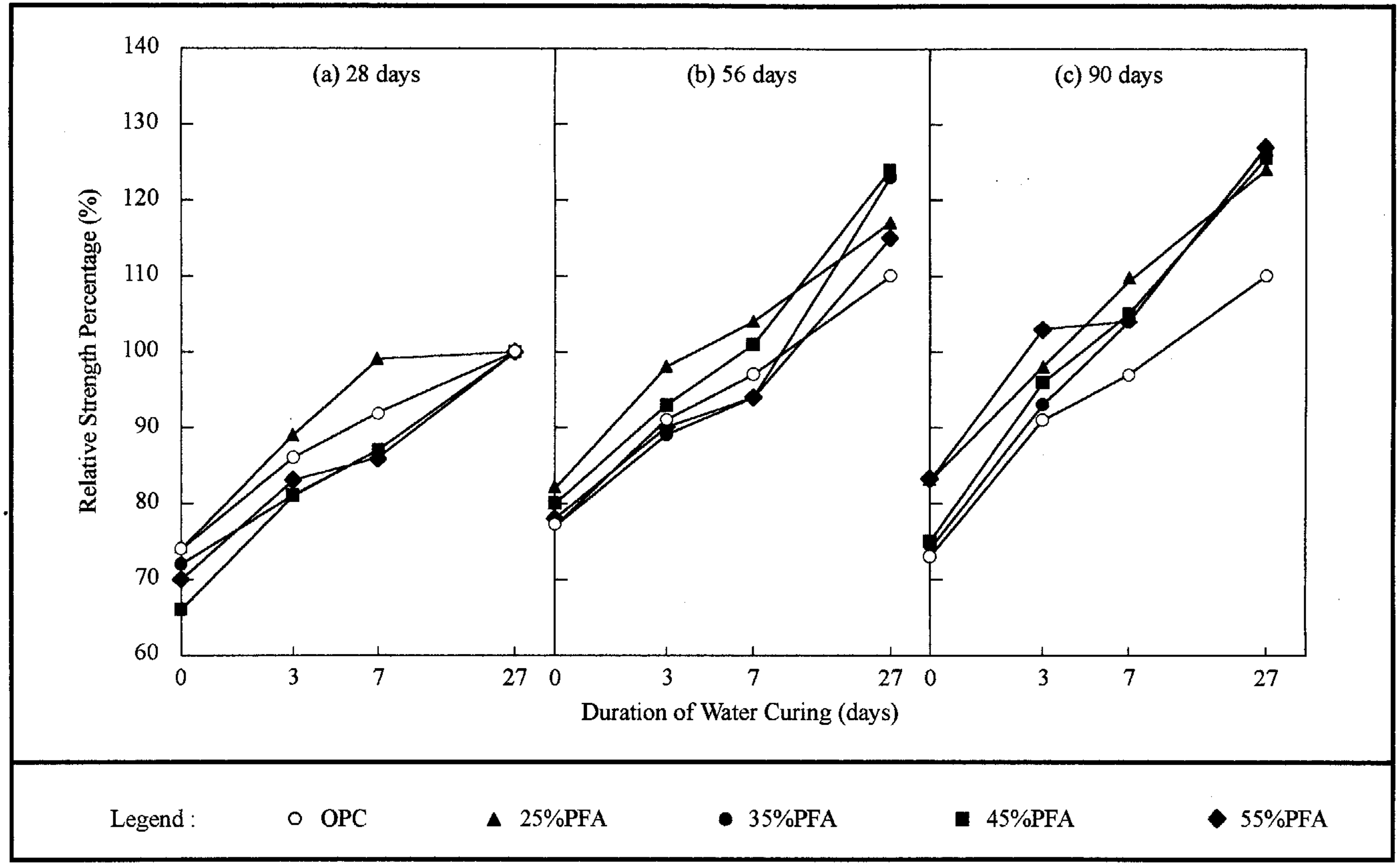

Figure 7 - Influence of Duration of Curing on Strength Development of Grade 30 OPC and PFA Concretes

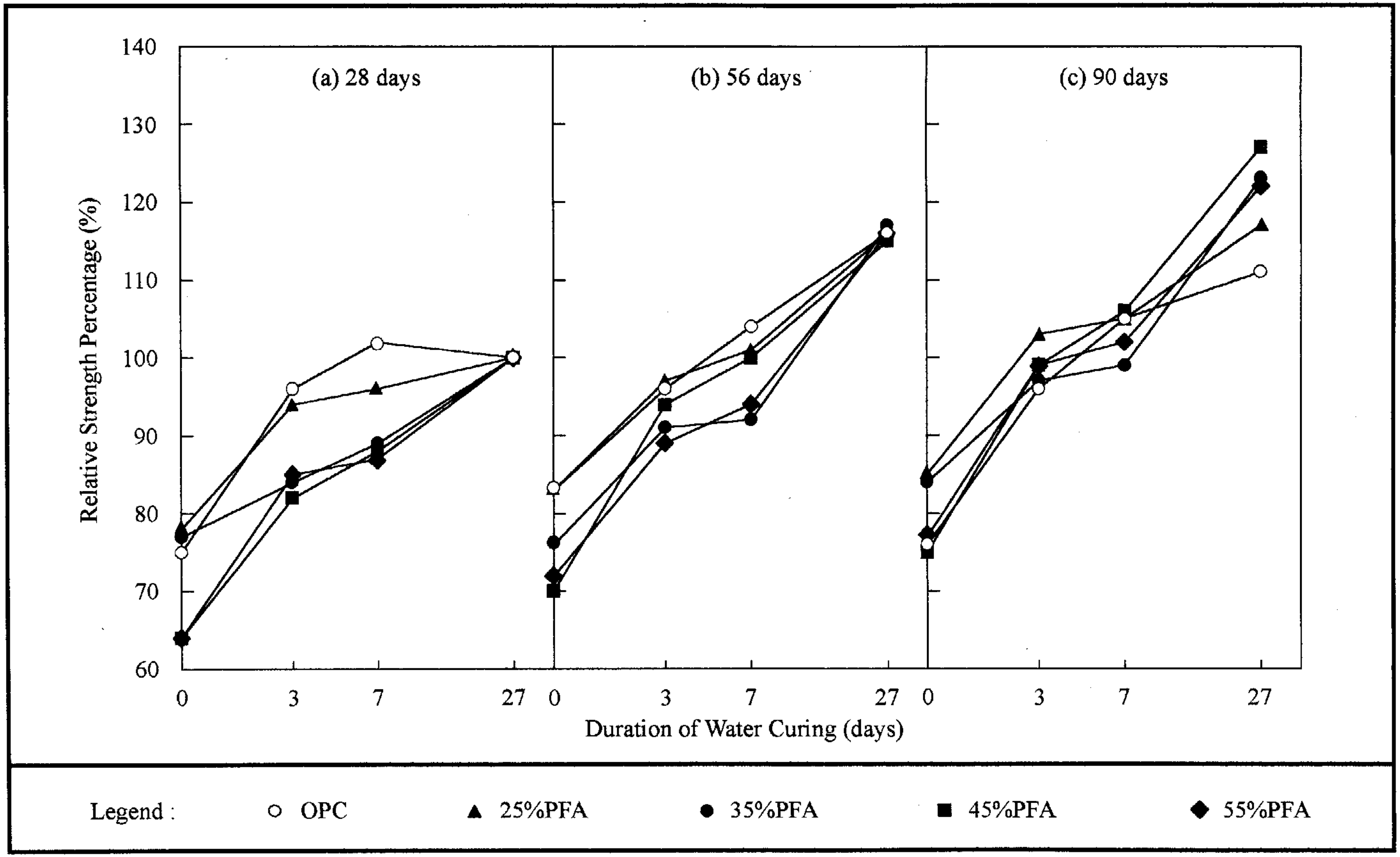

Figure 8 - Influence of Duration of Curing on Strength Development of Grade 45 OPC and PFA Concretes