ASEAN Journal on Science and Technology for Development Vol 18 No 2 (2001)

THE MECHANICAL PROPERTIES OF FLY ASH CONCRETE PREPARED AND CURED AT HIGH TEMPERATURES

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ABSTRACT

Results of an experimental investigation on the effect of fly ash content, water cement (w/c) ratio of concrete prepared and cured at temperatures of ambience, 40°C and 60°C are presented in this paper. The mechanical properties investigated here include its workability, its behaviour under compression and splitting tension. Microscopic investigations were also carried out using SEM micrographic images to gain understanding of concrete at its microstructural level.

The results indicate that high temperature increases early compressive strengths of concrete, but has decreasing effects on the strengths at later ages. The use of fly ash in concretes cast and cured at elevated temperatures improves the physical and mechanical properties of fresh as well as those of hardened concrete.

Various mathematical models describing the properties of such concretes are considered at the end of this paper. The strength properties of high temperature fly ash concrete were best represented by a simple exponential function of time, while its stress-strain relationship could be best described by an exponential function of strain of a more complicated form.

1. INTRODUCTION

In this last decade, a great number of research in high strength concrete using fly ash as partial replacement of cement has been widely carried out. In Indonesia, research in this field has in recent years also been active[1,2,3,4]. In most of those investigations, fly ash from industrial wastes has been utilised. Besari *et al.*[2] used fly ash from a coal firing power generating plant at Suralaya, a location at the western tip of the island of Java. They found the optimum value of fly ash to be approximately 15% of the cement weight, to obtain concrete having an average strength of fc' = 85 MPa. The specimens investigated were 100 x 200mm size cylinders, using a water cement ratio of 0.28 and applying superplasticisers. Previous studies have shown that under normal conditions, concretes using fly ash as partial replacement of cement have shown excellent properties such as better workability, less segregation and bleeding tendencies, greater strength, more solid, greater resistance to corrosion, higher density, more durable, better resistance to chemical and gas penetration, less shrinkage and creep, higher resistance against crack and a lower coefficient of heat transfer. These properties have been studied and reported by many investigators[1,5]. The effects of high temperature environment on fly ash concrete is however still a subject of much discussion[5,6,7,8,9]. This research therefore attempts to shed more light on concrete properties prepared and cured in hot environments.

2. RESEARCH SIGNIFICANCE

It is currently well known that high temperature environments significantly affect the properties of fresh as well as hardened concrete. Most of the research carried out to-date however, were carried out using regular concrete specimens, cured but not prepared at high temperatures. It is hoped that studies involving fly ash concrete prepared and cured at high temperatures will provide more knowledge to better support construction activities in countries with hot climate.

3. OBJECTIVES

The primary objectives of this study were :

(i) To evaluate the influence of fly ash and w/c ratios on the slumps and strength properties of fresh and hardened concrete, prepared and cured under high temperature environment.

(ii) To compare the performance of air-cured and water-cured fly ash concrete prepared in high temperature environments.

(iii) To derive mathematical models representing the observed behaviour of fly ash concrete, prepared and cured in high temperature environment.

4. EXPERIMENTAL PROGRAM

Two series of 100 x 200mm concrete cylindrical specimens were produced for this research. For the first series, concrete specimens were made using only Portland cement as binding material (NFA concrete), while for the second series, fly ash was added as a partial replacement of cement in the concrete (FA concrete). In this research, all materials used in producing, placing and curing of concrete were conditioned at temperatures of ambience (22°C to 27°C), 40°C and 60°C. To ensure an accurate w/c ratio in the design mix, the coarse and fine aggregates used in the mix for all temperature conditions were pre-dried in an oven 110°C for a duration of 24 hours. It is likely that after the drying process, the water content in the aggregates is 0% (zero percent). As in the general procedure commonly adopted, where coarse and fine aggregates are conditioned to an SSD (saturated surface dry) state, the control specimens used here were also prepared applying aggregates of SSD conditions at ambient temperatures, varying between 22°C and 27°C.

4.1. Mix composition

Composition of the concrete mixtures for both series 1 and 2 are shown in Table 1 and the physical properties of the concrete ingredients are tabulated in Table 2. Table 3 shows the chemical composition of type I cement and fly ash type F used in this study.

Table 1: Mix-design of concrete.

Material (kg/m³)	**FA Concrete**		**NFA Concrete**	
	w/c = 0.28	**w/c = 0.40**	**w/c = 0.28**	**w/c = 0.40**
Cement	475	476	560	560
Fly Ash	84	84	-	-
Water	156.8	224	156.8	224
SSD Water	54.86	46.36	54.86	46.36
Superplasticiser	7.45	-	6.21	-
FA (Sand)	643.33	478.19	643.33	478.19
C.A. (4.75-9.50) mm	437.76	437.76	437.76	437.76
C.A. (9.50-19.50) mm	567.52	567.52	567.52	567.52

Table 2: Physical properties of concrete ingredients.

Physical Properties (kg/l)	**Cement**	**Sand**	**Coarse Aggregate (mm)**	
			4.75-9.50	**9.50-19.50**
Apparent Specific Gravity	3.11	2.81	2.79	2.80
Bulk Specific Gravity (dry)	-	2.46	2.62	2.65
Bulk Specific Gravity (SSD)	-	2.58	2.68	2.70
Absorption (%)	-	5.15	2.39	1.98
Unit weight (dry rodded)	-	-	1.57	1.66
Unit weight loose (dry)	-	-	1.49	1.49
Fineness Modulus	-	2.79	-	-

Table 3: Chemical composition of type I cement and fly ash.

Chemical Composition		**Coarse Aggregate (mm)**	
		Type I Cement	**Fly Ash**
Silica Oxide	SiO_2	19.60	55.00
Ferro Oxide	Fe_2O_3	4.44	3.26
Aluminum Oxide	Al_2O_3	6.44	31.08
Calcium Oxide	CaO	64.31	3.25
Magnesium Oxide	MgO	1.04	1.06
Sulfur Trioxide	SO_3	2.15	0.62
Potassium	K_2O	0.95	-
Sodium	Na_2O	0.37	4.13
Loss in Ignition		2.76	-

Table 5: Compressive strength of concrete (MPa).

Temperature : Ambient ; Aggregate dry condition

Age	AAmN.28	AAmF.28	AAmN.40	AAmF.40	WAmN.28	WAmF.28	WAmN.40	WAmF.40
90 days	44.55	45.09	25.11	25.56	65.58	68.86	42.80	43.47
28 days	46.13	45.42	26.56	26.15	60.87	58.04	37.51	37.18
7 days	32.48	29.77	20.82	16.03	35.76	35.01	23.90	21.48
3 days	22.73	20.23	15.53	11.03	29.14	27.02	19.49	13.24

Temperature : 40°C

Age	A40N.28	A40F.28	A40N.40	A40F.40	W40N.28	W40F.28	W40.40	W40F.40
90 days	41.14	41.39	24.23	24.52	61.16	65.70	38.55	40.76
28 days	45.72	43.88	26.19	25.40	55.62	54.67	36.72	35.14
7 days	33.22	30.77	21.07	20.07	40.22	37.68	24.27	22.19
3 days	27.40	24.19	16.20	14.53	34.22	29.06	19.94	16.74

Temperature : 60°C

Age	A60N.28	A60F.28	A60N.40	A60F.40	W60N.28	W60F.28	W60.40	W60F.40
90 days	38.22	39.47	23.77	24.02	59.79	63.37	32.48	34.77
28 days	44.59	42.72	25.52	24.94	55.00	47.88	30.98	29.48
7 days	33.97	31.85	23.02	21.57	45.30	45.01	26.06	23.77
3 days	27.85	26.81	18.07	21.82	37.97	29.60	21.82	19.69

Control Specimens ; Temperature : Ambient ; SSD Aggregate

Age	AAmN.28	AAmF.28	AAmN.40	AAmF.40	WAmN.28	WAmF.28	WAmN.40	WAmF.40
90 days	46.17	46.88	27.98	28.02	75.57	76.82	48.84	50.25
28 days	47.92	46.63	28.23	28.10	70.07	69.32	43.43	42.72
7 days	38.80	32.56	24.90	16.57	52.71	46.42	25.73	23.52
3 days	32.39	27.31	18.86	11.70	32.97	28.35	19.78	14.91

Note :

1st place letter Indicating :	2nd & 3rd place letters Or digits indicating :	4th place letter Indicating :	Last two digits Indicating :
Curing condition	*Temperature*	*FA content*	*Water/Cement ratios*
A = Air-cured	Am = Ambient	F = FA concrete	.28 = W/C = 0.28
W = Water-cured	40 = 40°C	N = NFA concrete	.40 = W/C = 0.40
	60 = 60°C		

higher temperature environments. Continued cement hydration and secondary chemical reactions of free calcium and silica from FA, which proceeds at a slower rate, are commonly considered as strength improvement mechanisms[1,2,9].

An interesting observation could also be made from the same set of data obtained. The specimens exposed to air at higher temperatures show lower strengths tested at 90 days than those tested at 28 days. There is a strong tendency of decreasing rates of growth in strengths at later ages in concretes exposed to air at higher temperatures. This might be due to the low relative humidity existing around the specimen during its curing process at

Table 6: Splitting strength of concrete (MPa).

Temperature : Ambient

Age	AAmN.28	AamF.28	AAmN.40	AAmF.40	WAmN.28	WAmF.28	WAmN.40	WAmF.40
90 days	4.85	5.08	2.66	2.75	7.23	7.50	4.80	4.38
28 days	5.00	5.01	2.85	2.81	6.62	6.38	4.17	3.74
7 days	3.50	3.23	2.24	1.71	3.85	3.79	2.64	2.17
3 days	2.44	2.18	1.66	1.19	3.16	2.94	2.15	1.33

Temperature : 40°C

Age	A40N.28	A40F.28	A40N.40	A40F.40	W40N.28	W40F.28	W40N.40	W40F.40
90 days	4.39	4.41	2.61	2.63	6.61	7.01	4.25	4.08
28 days	4.87	4.71	2.82	2.74	6.04	5.88	4.06	3.52
7 days	3.57	3.35	2.26	2.15	4.33	4.06	2.68	2.22
3 days	2.90	2.57	1.74	1.57	3.72	3.10	2.24	1.68

Temperature : 60°C

Age	A60N.28	A60F.28	A60N.40	A60F.40	W60N.28	W60F.28	W60N.40	W60F.40
90 days	4.12	4.20	2.54	2.58	6.43	6.51	3.52	3.41
28 days	4.80	4.57	2.72	2.68	5.87	5.32	3.37	2.93
7 days	3.66	3.41	2.45	2.28	5.03	4.90	2.90	2.41
3 days	3.00	2.86	1.94	1.92	4.27	3.25	2.42	2.01

Control Specimens ; Temperature : Ambient ; SSD Aggregate

Age	AAmN.28	AAmF.28	AAmN.40	AAmF.40	WAmN.28	WAmF.28	WAmN.40	WAmF.40
90 days	4.91	5.00	3.01	2.96	8.17	8.20	5.54	5.07
28 days	5.15	5.07	3.04	2.86	7.53	7.39	4.82	4.36
7 days	3.95	3.48	2.63	1.79	5.73	5.03	2.87	2.41
3 days	3.42	2.91	2.04	1.30	3.58	3.07	2.18	1.51

Note :

1st place letter
Indicating :
Curing condition
A = Air-cured
W = Water-cured

2nd & 3rd place letters
Or digits indicating :
Temperature
Am = Ambient
40 = 40°C
60 = 60°C

4th place letter
Indicating :
FA content
F = FA concrete
N = NFA concrete

Last two digits
Indicating :
Water/Cement ratios
.28 = W/C = 0.28
.40 = W/C = 0.40

high temperatures, which impedes the process of further hydration in the concrete. The relative humidity in the curing box is represented by the curve shown in Figure 1. After about 28 days, there apparently was insufficient moisture left in the specimen capillaries for continuing hydration process. It has been established that hydration can take place when the vapour pressure in the concrete capillaries is sufficiently high, i.e. equal or more than approx. 0.8 of the saturation pressure[10]. For these reasons, the same phenomenon was not observed in the cases of water cured specimens, where higher strengths were consistently produced.

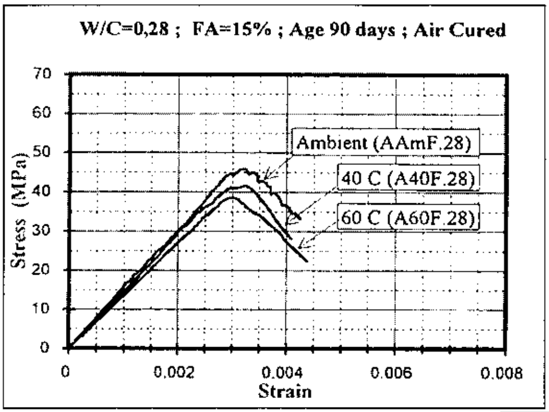

Figure 2: Stress-strain curve of concrete.

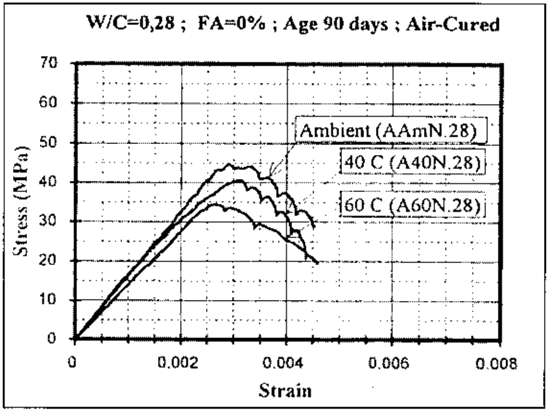

Figure 3: Stress-strain curve of concrete.

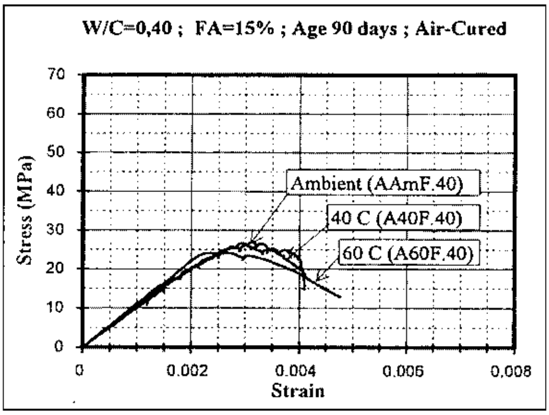

Figure 4: Stress-strain curve of concrete.

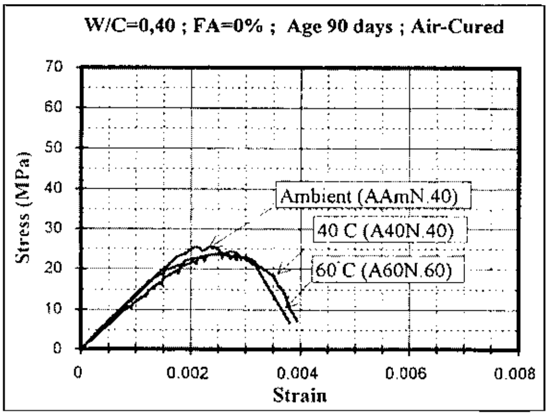

Figure 5: Stress-strain curve of concrete.

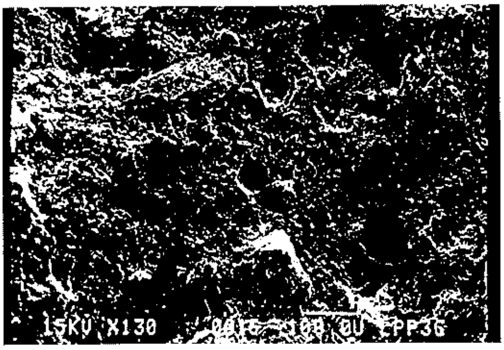

Figure 6: Micrograph of 40°C concrete mortar, showing a more uniformly distributed finer pores.

Figure 7. Micrograph of 60°C concrete mortar, showing a coarser pore distribution.

6. MATHEMATICAL MODELS

To facilitate future applications of the experimental results obtained, attempts were made to represent the observed properties of high temperature fly ash concrete in mathematical forms. For the purpose of strength modeling, five types of mathematical expressions have been considered, specifically, $f = a\ t^b$, $f = a + b \log t$, $f = a - a\ e^{-bt}$, $f = a + b\ t + c\ t^2$ and $f = a\ t + b\ t^2$, where f represents the compressive of tensile strength of the concrete, t describes the time variable while a, b and c stand for unknown constants. These constants were determined by a regression process of the available data such that the best fit, corresponding to Residual of Squares value (R-Squares) closest to 100%[11], prevails.

The third expression, i.e. of the type $f = a - a\ e^{-bt}$ produced the best fit to the obtained test data[8] with values of R-Square varying between 88.09% and 99.56% for both compressive as well as tensile strengths. The values of the constant "a" varies between 23.58 and 64.41 for compressive strengths and varies between 2.578 and 7.048 for splitting strengths. The values of the constant "b" varies between 0.105 and 0.835 for compressive strengths and varies between 0.106 and 0.443 for splitting strengths.

To model the stress-strain relationship of the various concretes being investigated at the age of 90 days, again five types of mathematical expression were considered, specifically $f_c = a\,\varepsilon^b$, $f_c = a + b \log \varepsilon$, $f_c = a - a\,e^{-b\varepsilon}$, $f_c = a\,e^{-b\varepsilon}\,\varepsilon^c$ and $f_c = a\,\varepsilon = b\,\varepsilon^2$, where f_c and ε represent concrete stress and strain respectively, while a, b and c stand for unknown constants. The constants were defined in a manner similar to those of the strength expressions. The fourth equation, i.e. of the type $fc = a\ e^{-b\varepsilon}\ \varepsilon^c$ produced the best fit to the obtained test data[8], with values of R-Square varying between 88.25% and 99.66%. Here the parameters "a", "b" and "c" vary between 4.6×10^5 and 1.03×10^{10}, 509.42 and 1205.19 and between 1.430 and 2.92 respectively. Table 7 shows regression result for the values of the constant a, b and c with their corresponding values of R-Square. Figures 8 and 9 show representative curves of strength as functions of time for air cured concretes. The two curves in both figures represent cases of high and low R-Square values. Figures 10 and 11 show similar cases for water cured concretes. Figure 12 shows the curve of the mathematical model representing obtained stress-strain data of fly ash concrete exposed to air. It may be observed how well the curves fit the obtained test data.

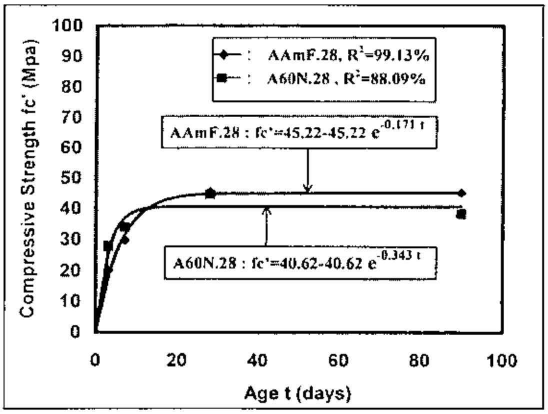

Figure 8: Mathematical model for compressive strength of concrete, air cured; W/C = 28.

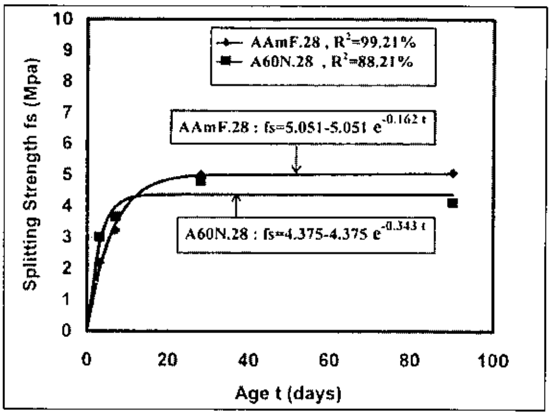

Figure 9: Mathematical model for splitting strength of concrete, air cured; W/C = 0.28.

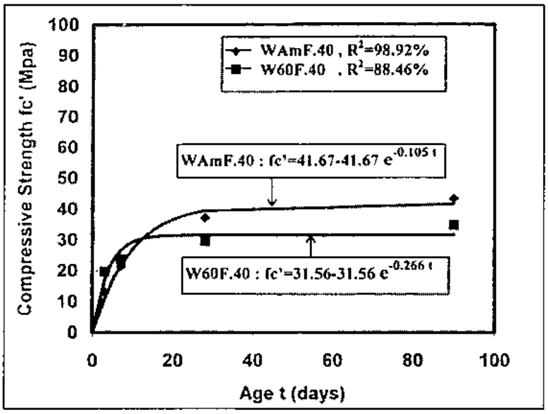

Figure 10: Mathematical model for compressive strength of concrete, water cured ; W/C = 0.40.

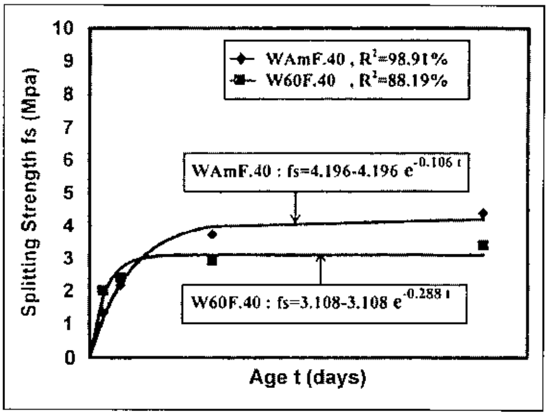

Figure 11: Mathematical model for splitting strength of concrete, water cured; W/C = 0.40.

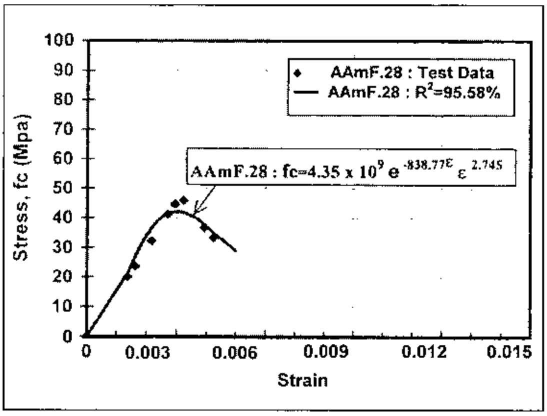

Figure 12: Mathematical model for stress-strain of air cured FA concrete ambient temperature; W/C = 0.28; Age 90 days.

7. CONCLUSIONS

Several general conclusions drawn from this investigation, may be summarised as follows:

(i) Concrete prepared in high temperature environments produce smaller slumps, indicating greater stiffness of fresh concrete. This feature needs special attention when producing concrete in high temperature areas, since difficulties may arise during casting and compaction, which may lead to unsatisfactory concrete with honey combs. Fly ash can be effectively used to enhance slump and workability of fresh concrete.

(ii) The application of fly ash produces higher strength concretes, irrespective of the method and temperature of curing.

(iii) Water curing, irrespective of the temperature, produces concrete with higher strength than exposed to air at similar temperature settings.

(iv) High temperature increases early strengths of concrete, but has a reversed effect on the strength at later ages.

(v) Exposure to air at high temperatures produces maximum strengths around age 28 days in NFA as well as FA concretes. At later ages, their strengths stay practically constant or may even decrease slightly.

(vi) Higher temperatures, water/cement ratios and curing conditions affect the splitting strength of concrete in the same way they affect the compressive strength.

(vii) The compressive strength of high temperature NFA concrete water cured, continues to increase beyond the age of 28 days, indicating a continuing hydration process of cement in the concrete. The rate of growth in strength after 28 days is more pronounced in FA concrete than that in NFA concrete, indicating, beside the hydration process of cement, a secondary reaction between free lime and fly ash silica is also taking place in FA concretes, which proceeds at slower rate.

(viii) Higher curing temperatures produce FA concretes as well as NFA concretes with stress-strain curves showing a lower ultimate stress.

(ix) Higher water/cement ratios produces FA concretes as well as NFA concretes with stress-strain curves showing a lower ultimate stress irrespective of their curing temperatures.

(x) Higher curing temperatures tend to produce concretes with less uniformly distributed coarser pores than produced in concretes cured at lower temperatures.

(xi) The mathematical model that best represents both the compressive as well as the splitting strength of the various concretes investigated, is of the type $f = a - ae^{-bt}$, and those representing the stress-strain curves at age of 90 days of the type $f_c = ae^{-b\varepsilon} \varepsilon^c$.

(xii) This research needs to be expanded to include temperatures beyond 60°C to gain better quantitative understanding of the effects of preparing and curing at high temperatures on the hardening process and the mechanical properties of FA concretes as well as NFA concretes.

8. ACKNOWLEDGEMENT

The authors would like to take this opportunity to express their appreciation to the Indonesia Toray Science Foundation (ITSF) which made generous grants available, without which this research would not be possible. The authors are also deeply indebted to the Laboratory of Structures and Materials of Institut Teknologi Bandung for its enthusiastic support in the liberal use of its premises and supplies, which greatly facilitated the investigation process. To colleagues and members of other co-existing research teams, the authors would like to thank them for their lively comments and discussions during the preparation of the text.

9. REFERENCES

1. Besari M.S., Munaf D.R., Hanafiah, Iqbal M.M. (1996), "Optimum Value of Fly Ash and Interface Density Behavior of High Performance Fly Ash Concrete", International Symposium on Utilisation of High-Strength/High Performance Concrete, Paris-France.
2. Besari M.S., Munaf D.R., Hanafiah (1992), "The Effect of Fly Ash and Strength of Aggregate to The Mechanical Properties of High Strength Concrete", International Conference of Concrete and Structures, Singapore.
3. Iqbal M.M., Hanafiah, Iskandar (1996), "The Effect of High Temperature Environments on The Compressive Strength of Concrete" ITSF Report, Jakarta.
4. Kadir I. (1996), "The Effect of High Temperature Environments on The Mechanical Properties of Concrete", M.S. Thesis, Institut Teknologi Bandung, Indonesia.
5. CUR (1991), "Fly Ash as Addition to Concrete", INTRON, Institute for Material and Environmental Research B.V.A.A. Balkema, Rotterdam.
6. Fip-Stupo, "Concrete in Hot Countries", The Dutch Member Group of FIP.
7. Fookes, D.J. Pollock, E.A. Kay (1987), "Concrete in the Middle East", A View Point Publication (12.077) part 2 from Magazine Concrete.
8. Soroaka I, (1993), "Concrete in Hot Environment", E & FN Spon, London.
9. Cuijuan, S., Luoshu, G. And Haimin, W., (1986), "Concrete Made with Calcium-Enriched Fly Ash", Proceedings Second International Conference, Madrid, Spain, Volume 1, ACI SP-91, V.M. Malhotra Editor, pp. 387 - 411.
10. A.M. Neville (1991), "Properties of Concrete", ELBS Singapore.
11. Mandel, J. (1984), "The Statistical Analysis of Experimental Data", Dover.