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BUILDING RESEARCH CENTRE

PROPERTIES OF FRESH AND HARDENED CONCRETE WITH THE TERNARY BINDER SYSTEM CONTAINING TWO SUPPLEMENTARY CEMENTITIOUS MATERIALS

RESEARCH REPORT

Report Prepared by the
Building Research Centre

on

PROPERTIES OF FRESH AND HARDENED CONCRETE WITH THE TERNARY BINDER SYSTEM CONTAINING TWO SUPPLEMENTARY CEMENTITIOUS MATERIALS

for

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EXECUTIVE SUMMARY

This report summarises the research work on concrete with the ternary binder system, in which two supplementary cementitious materials (SCMs) are incorporated into the binder with portland cement. In the other high performance concrete research report (HPC-2), the work on concrete with the binary binder system containing one of the three SCMs, silica fume, fly ash and slag, has been published by the Building Research Centre (BRC) recently. Both research projects have been financially supported by the NSW Roads and Traffic Authority.

An experimental program was carried out to investigate the properties of fresh and hardened concrete of nine concrete mixes. Six mixes were comprised of two types of ternary binders, silica fume plus fly ash (SF+FA) or slag plus fly ash (SG+FA); three control mixes contained only Type GP ordinary portland cement (PC). The main parameters in the concrete mixes are: water to binder ratio (w/b of 0.35 and 0.40), binder content (400, 450 and 500 kg/m^3) and the equal-mass replacement ratios of the SCMs (8% SF, 20% or 30% FA and 35% or 50% SG).

All the nine mixes were evaluated to assess water demand and slump loss. Seven of the nine mixes were also evaluated for setting time, bleeding and temperature development during hydration. The compressive strength of each concrete mix was tested at the age of 3, 28 and 91 days. The durability performance of the concrete mixes was investigated extensively. While eight concrete mixes were tested for their sulphate resistance and carbonation rate, all the nine mixes were investigated for water absorption and were subjected to the three types of chloride penetration tests: static ponding, cyclic ponding (wet-and-dry) and the rapid chloride permeability test (ASTM C1202).

Overall, the test results indicated that the influences of the SCMs on concrete performance varied according to the characteristics of the SCMs and their replacement levels. In general, the influences of two SCMs in a ternary mix are more complex than that of a single SCM in a binary mix. However, in many of the tests in this investigation, the performance of a ternary mix appeared to be an amalgam compromising of the performances of the two binary mixes containing each of the two SCMs.

The water demand of the SF+FA and SG+FA ternary concrete was found to be higher than that of the PC concrete and the binary fly ash concrete, but lower than that of the binary silica fume concrete.

The ternary SF+FA concrete had a similar or a lower slump loss than the PC concrete; the slump loss was about the average of that of the silica fume and fly ash binary concrete. The ternary SG+FA concrete had a higher slump loss than the PC concrete and an increase in the slag content resulted in an increase in slump loss.

Both types of ternary concrete recorded a much longer setting time than the PC concrete, especially the ternary SG+FA concrete. While both ternary concretes also had higher bleeding than the PC concrete, the SF+FA concrete exhibited a lower bleeding than that of the binary concrete containing only fly ash.

The temperature rise in the ternary SF+FA and SG+FA concretes was much lower than that in the PC control concrete. Not only the maximum temperature, but also the slope of the temperature rise and fall was reduced significantly.

With equal-mass replacement of PC by SCMs, the ternary SF+FA and SG+FA mixes generally had a lower compressive strength than the PC concrete of the same w/b ratios at 3, 28 and 91 days. However, the relative strength of a ternary mix compared to its PC control mix increased with concrete age and was close to 1.0 at 91 days.

All the nine mixes were examined with the rapid chloride permeability test (ASTM C1202) at 28 and 182 days. Both types of ternary concrete recorded a much lower electrical charge at 28 days (at ratios of 0.32 to 0.47) and an extremely lower charge at 182 days (at ratios of 0.10 to 0.17) when compared to the PC control mixes.

Five chloride ponding tests were carried out for all the nine concrete mixes: a static ponding test in 3% NaCl solution at 28 days over 91 days, the 15% NaCl static ponding tests at 28 and 182 days over 14 days and 15% NaCl wetting-and-drying cyclic ponding tests at 28 and 182 days over 14 days. At the end of a 14 or 91-day test duration, the prism specimens were broken at the middle and the broken section was sprayed with silver nitrate solution. The depth of the water-soluble chloride penetration was determined by a colour change on the section due to the formation of a white precipitate of silver chloride.

Both ternary mixes recorded a lower chloride penetration than the PC control with the ratios of 0.76 to 0.93 in the 91-day static ponding test.

The use of a 15% NaCl solution in the ponding tests accelerated the chloride penetration into concrete in shorter test duration. Higher chloride penetration was observed in the concrete specimens tested at 182 days compared to those tested at 28 days when specimens were stored in air at 23 1C between 28 to 182 days. The increase in chloride penetration with age was more pronounced in the PC concrete than in the ternary concrete. In general, both ternary concretes recorded a lower chloride penetration than the PC control concrete in the 14-day ponding test at the age of 182 days; however, two of the three SG+FA mixes recorded a higher chloride penetration than the PC control in the test at 28 days.

Except in submerged structures, wetting-and-drying cyclic ponding tests simulate closely the processes of chloride ingress into concrete in marine environments. Cyclic ponding tests also accelerate chloride penetration rate and therefore reduce the test duration. Both ternary concretes had a lower chloride penetration than the PC control in the 14-day wet-and-dry cyclic ponding test at 182 days. However, two of the three SG+FA mixes recorded a higher chloride penetration than the PC control in the test at 28 days.

The above seven chloride penetrability tests can be classified into two groups; one group consists of the two ASTM C1202 tests at 28 or 182 days and the other group consists of the five static and cyclic chloride ponding tests. The statistical analyses of the correlation coefficients indicated a significant difference between the two groups of tests. In general, the correlation coefficient between the two tests within a group was much higher than that between two tests of different groups.

The statistical correlations between the compressive strength and the results of all the chloride tests were also found to be very poor. It demonstrates that compressive strength should not be used as the guide for durability of concrete in marine environments.

Since chloride penetration into concrete is strongly influenced by exposure conditions, it would be sensible to select a test method according to the environment of the field concrete. While static chloride ponding tests are most suitable for testing concretes in submerged marine structures, cyclic ponding tests are suitable for testing concretes in other marine environments. Wet-and-dry cycles simulate the chloride penetration process not only in the splash and tidal zones but also in a general marine atmosphere in which the penetration of airborne chlorides into concrete is promoted similarly through wet-and-dry cycles. Although the ASTM C1202 test has the advantage of a short test duration, the theoretical basis and the correlation between a measured electrical charge and the chloride penetrability need to be further verified.

The water absorption test in this investigation was carried out under several preconditions and test ages viz, air-dried at 28 days, oven-dried at 28 and 182 days. At 28 days, the oven-dry water absorption values were several times higher than the air-dry water absorption values. All the ternary mixes had lower oven-dry water absorption than the PC mixes, while they recorded much higher air-dry water absorption compared to the PC mixes. At 182 days and with the same specimens as used at 28 days, the oven-dry water absorption was only slightly different to the oven-dry results at 28 days.

The statistical results indicate that, while the air-dry water absorption had a very poor correlation with the chloride penetrability tests, the oven-dry absorption results had a much better correlation with the chloride test results. However, since water absorption does not allow for the effects of chloride diffusion and chloride binding, the use of water absorption to indicate concrete durability in marine environments is questionable. Further work is recommended in this area, and a "salt water absorption and chloride penetration test”, which can correlated the water absorption and chloride penetration results based on the same specimen, is proposed.

Eight of nine concretes were tested for their carbonation rate in an accelerated laboratory test. In general, the carbonation depth in the ternary mixes was much higher than that in the PC mixes. The ternary concrete was also found to have a higher carbonation rate than the binary concrete containing one of the two SCMs of the same content.

The same eight mixes were also investigated for sulphate resistance based on ASTM C1012 method. The ternary SCM mixes recorded excellent and much better performance compared to the PC control mixes.

In summary, this work together with the binary concrete research has investigated the properties of fresh and hardened concretes containing one or two SCMs. It was found that there was a significant improvement in the durability performance of the SCM concretes in marine environments. On the other hand, a few possible negative effects in concrete performance were also identified, such as the higher carbonation rate, higher bleeding and retarded setting of SCM concrete containing fly ash and/or slag. These properties need to be carefully dealt with in the mix design and field construction applications.

Further research work is recommended on the three areas: the chloride penetration tests and assessment criteria for performance specifications, the optimal mix design of SCM concretes and further details of the effects of SCMs on concrete properties.

1. INTRODUCTION

Over the last two decades, the application of Supplementary Cementitious Materials (SCMs) such as silica fume, fly ash and ground granulated blast-furnace slag has increased significantly. SCMs have the dual benefits of saving energy and resources, as well as significantly improving concrete performance. Concrete mixtures incorporating SCMs have superior resistance to thermal cracking, are durable in the presence of aggressive chemicals and provide better protection to reinforcing steel against corrosion. Today, a so-called 'high performance concrete' almost invariably contains one or more SCMs and usually a superplasticiser as well. It can be anticipated that the use of SCMs in concrete will continue to increase in the future.

However, the physical and chemical characteristics of SCM concretes are quite different to those of ordinary portland cement (PC) concretes. Extensive research is needed to further understand the fundamental effects of SCMs on the properties of concrete and the mechanisms of these influences. It is also a fact that the properties of SCM concretes vary significantly from different sources. Experimental investigation is needed to examine the impact of using local SCMs on a wide range of concrete properties before the materials can be used extensively and with full confidence in construction.

Current research at the BRC sponsored by the Roads and Traffic Authority of New South Wales covers the investigation of the properties of concretes containing one SCM (binary binder system) and two SCMs (ternary binder system) in binder systems. The work reported here is the investigation of concretes with a ternary binder system. The investigation of binary concrete mixes has been reported separately (Chang et al, 1998).

A total of nine concrete mixes consisting of six ternary mixes and three PC control mixes were investigated. Experimental tests were carried out to examine a wide range of properties of fresh and hardened concretes. This report summarizes the experimental procedures and test results of this research work.

A Project Steering Committee was established in consultation with the RTA of NSW to provide technical guidance for the project. The details of the test arrangement, test methods, curing regimes and mix design were reviewed by the Steering Committee. Some modifications were recommended and the final test program was endorsed by the Steering Committee.

2. EXPERIMENTAL PROGRAM

An experimental test program was carried out to investigate the properties of nine concrete mixes, of which six had ternary binders and three, the control mixes, had ordinary portland cement (Type GP).

The comparisons between a ternary mix and a control mix are based on the equal-mass replacement some of the portland cement (PC) in the binder by two SCMs. An important advantage of this test arrangement is that the effects of replacing PC with SCMs on concrete properties are evaluated with the ternary mix and the PC mix of the same binder content and water to binder ratio.

A wide range of properties of fresh and hardened concretes was investigated in this experimental work. The emphasis was placed on the durability performance of the concrete mixes. Various durability tests, including four chloride penetration tests were carried out to establish the significance of the tests and their correlations. The effects of specimen age and test duration on the durability test results were also investigated.

Discussions with the Project Steering Committee included details regarding the curing regimes and pre-conditioning methods for the test specimens. Section 2.5 describes the curing regimes for the specimens as well as some of the modifications on testing and pre-conditioning procedures in the sulphate resistance test and water absorption test.

Table 2.1-1 outlines the total experimental test program, including the test variables and test arrangements for each of the nine mixes investigated. The selected mix parameters are highlighted with black squares and the selected tests are marked with "Y" in Table 2.1-1.

This project was part of the BRC-RTA high performance concrete (HPC) research program, which included a parallel research project on properties of concrete with a binary binder system (the binder containing one of the three SCMs: silica fume, fly ash and slag). Twenty-one concrete mixes were investigated in the binary concrete project. Therefore, it was decided that the concrete mixes in the ternary concrete project be numbered from Mix-22 to Mix-30, as shown in Table 2.1-1. The PC control mix M-22 was indeed identical, in the mix proportion, to M-3 in the binary concrete investigation. However, the experimental test program was not the same in the binary and ternary concrete projects. Therefore, the mix number M-22 was used in this ternary project, although some of the test results were obtained from the tests in the binary concrete investigation.

The following sections of this chapter describe details of the test program, the test methods, the materials used in the mixes, the mixing of concrete and the casting and curing of the specimens.

Table 2.1-1 Test Program and Variables of Nine Ternary and PC Control Concrete Mixes

Binder Type			OPC (Type GP)			OPC +Slag +Fly Ash			OPC +SF +Fly Ash		
Binder Content (kg/m^3)		400	■						■		
		450		■		■				■	■
		500			■		■	■			
W/B ratio (SSD aggregates)		0.35		■	■	■	■	■		■	■
		0.40	■						■		
OPC Type		Ordinary Portland Cement - Type GP	░	░	░	░	░	░	░	░	░
OPC Content (%)		Type GP (%)	100	100	100	30	45	30	62	72	62
Silica Fume Content (%)											
		8%							■	■	■
Fly Ash Content (%)		20%				■	■	■		■	
		30%							■		■
GGBFSlag Content (%)		35%					■				
		50%				■		■			
Admixture		Water Reducer + Superplasticiser	░	░	░	░	░	░	░	░	░
Experimental Tests Arrangement	1	Slump Loss over 30 Minutes (AS1012)	Y	Y	Y	Y	Y	Y	Y	Y	Y
	2	Setting Time (AS1012)	Y	Y	Y		Y	Y	Y		Y
	3	Bleeding (AS1012)	Y	Y	Y		Y	Y	Y		Y
	4	Temperature Development in Concrete	Y	Y	Y		Y	Y	Y		Y
	5	3,28 &91 day Compressive Strength f'c (AS1012)	Y	Y	Y	Y	Y	Y	Y	Y	Y
	6	Chloride-Permeability (ASTM C1202) - at 28 days	Y	Y	Y	Y	Y	Y	Y	Y	Y
	7	Chloride-Permeability (ASTM C1202) - at 182 days	Y	Y	Y	Y	Y	Y	Y	Y	Y
	8	Static ponding -1 (3% NaCl at 28d over 91days)	Y	Y	Y	Y	Y	Y	Y	Y	Y
	9	Static ponding -2 (15%NaCl at 28d over 14 days)	Y	Y	Y	Y	Y	Y	Y	Y	Y
	10	Static ponding -3 (15%NaCl at 182d over 14 days)	Y	Y	Y	Y	Y	Y	Y	Y	Y
	11	Cyclic ponding -1 (15%NaCl at 28d over 14 days)	Y	Y	Y	Y	Y	Y	Y	Y	Y
	12	Cyclic ponding -2 (15%NaCl at 182d over 14 days)	Y	Y	Y	Y	Y	Y	Y	Y	Y
	13	Water Absorption at 28 day over 3 days	Y	Y	Y	Y	Y	Y	Y	Y	Y
	14	Water Absorption at 182 day over 3 days	Y	Y	Y	Y	Y	Y	Y	Y	Y
	15	Sulphate Resistance (ASTM C1012)	Y	Y	Y	Y	Y	Y	Y		Y
	16	Carbonation (8% CO2 at 28d over 28 and 56 days)	Y	Y	Y	Y	Y	Y	Y		Y
Concrete Mix Number			**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**

2.1 TEST VARIABLES

The variants in the concrete mixes were designed to achieve the following objectives:

- to improve concrete performance, especially durability performance, through the use of ternary binders with relatively lower water to binder ratio and higher binder content
- to investigate the properties of fresh and hardened concrete with two types of ternary binders
- to investigate the effect of varying proportions of the two SCMs in a ternary binder on the properties of concrete
- to investigate the effect of binder content on the properties of concrete with ternary binders
- to compare the test results of each ternary mix with that of a PC control mix with the same w/b ratio and binder content.

Based on these objectives, nine concrete mixes were designed as shown in Table 2.1-1.

2.1.1 BINDER TYPES AND REPLACEMENT RATIO OF SCMs

The three SCMs used in the ternary binders were silica fume (SF), fly ash (FA) and ground granulated blast furnace slag (SG). Concrete mixes with two types of ternary binders were investigated. These two ternary binders were the combinations of PC+SF+FA and PC+SG+FA.

Control concrete mixes with only portland cement (Type GP) in the binder were included to help evaluate the performance of the ternary mixes.

The incorporation of each of the two SCMs in a ternary binder was based on an equal-mass replacement of portland cement. The content of a SCM was indicated by the percentage by mass in the total binder. Three mixes with the PC+SF+FA ternary binder had the same fly ash content of 20%, while one mix also had 35% of slag and the other two had 50% slag. Another three mixes with the PC+SG+FA ternary binder had the same silica fume content of 8%, while the fly ash content was 20% or 30%.

The silica fume and fly ash in a concrete mix with the ternary binder of PC+SF+FA was batched separately and added with the Type GP cement into the mixer during the concrete mixing. For the PC+SG+FA ternary binders, the commercial blended slag cement with 65% slag or 35% PC was used to obtain the required slag content in a mix. The required fly ash content and the additional quantity of the Type GP cement (besides the quantity in the slag blended cement) were batched separately and added to the mixer together with the other ingredients during the concrete mixing.

2.1.2 BINDER CONTENT AND W/B RATIO

The binder content for the PC+SF+FA ternary mixes was 400 kg/m^3 or 450 kg/m^3, and the w/b ratio was 0.4 or 0.35 respectively. For the PC+SG+FA ternary mixes, the binder content was 450 or 500 kg/m^3, and the w/b ratio was 0.35 in both cases.

Relatively high binder contents and low w/b ratios were used in this program to meet the RTA's objectives of achieving a high durability performance of ternary concretes for potential applications in marine environments.

2.1.3 WATER REDUCER AND SUPERPLASTICISER

The chemical admixtures used in this experimental work are MBT products, a water reducer Pozzolith 370 and a compatible superplasticiser Rheobuild 1000.

The chemical admixtures can be added to the concrete mixes either in a fixed dosage ratio or varied dosage ratio in relation to the unit binder content. When variable dosage ratios are adopted, a criterion is needed to control the admixture addition. A measurement of the consistency of the fresh concrete, such as slump, is often used as such a criterion.

The advantage of using a fixed dosage ratio of admixtures is that the effect of admixtures on the properties of the concrete can be evaluated based on the equal dosage rate. However, in the investigation of a series of concrete mixes with different binder types and varied water content, the use of a fixed dosage ratio may result in some very dry or wet mixes, which are not acceptable in practice. In view of the need for practical application, it was decided to use variable admixture dosage ratios, and to use a target slump as the criterion for the control of admixture addition.

A target slump of 80 ±20 mm was set for the control of dosing the water reducer and superplasticiser in the concrete mixes. To achieve the target slump, the gradual addition of the water reducer was the first step. The maximum dosage ratio of the water reducer was set as 400-ml per 100kg of cementitious content. This is in accordance with the manufacturer's recommendation. If the slump of a mix was still lower than the target slump after the addition of the maximum dosage of water reducer, then the superplasticiser was gradually added to the mix, until the target slump was achieved.

2.1.4 TEST ARRANGEMENT

This test program investigated a wide range of properties of both fresh and hardened concrete. Table 2.1- 1 contains a total of sixteen tests, summarizes the test program and describes the test arrangement.

As it is shown in Table 2.1-1 ten of the experimental tests were carried out on each of the nine mixes, while the other six tests were carried out on seven or eight concrete mixes.

In this test arrangement the emphasis was on the durability tests, especially in the chloride penetration tests. The chloride related corrosion of reinforcing steel in concrete structures is a major concern for concrete construction in marine environments. One of the main objectives, in the development of high performance concrete containing supplementary cementitious materials, is to enhance the resistance of concrete to chloride ingress.

However, currently there are few test methods which are widely accepted for the evaluation of concrete against chloride ingress, especially when the concretes contain SCMs. Therefore, several chloride penetration test procedures were incorporated in this investigation. Through the comparison of the test results, the correlation between the tests and the significance of the test ages are to be assessed. This will help to further develop practical chloride penetration test procedures for concrete specifications and quality control.

2.2 TEST METHODS

The standard test methods are only referred to as the relative standards without any detailed description of the procedures. The test methods are described as follows.

2.2.1 SLUMP

The concrete slump test was carried out according to the procedures in AS 1012, Part 3. The target initial slump of the concrete was measured between 4 and 8 minutes after the mixing of water into the concrete batch. Another slump test was carried out 30 minutes after the initial slump measurement. The slump loss in this project is defined as the difference between these two slump measurements.

2.2.2 SETTING TIME

The setting time of fresh concrete was determined according to AS 1012, Part 18, based on mortar samples sieved out of concrete through 4.74 mm sieves. The time of initial setting and final setting were determined from two mortar samples.

2.2.3 BLEEDING

The bleeding of concrete was determined according to AS 1012, Part 6, based on one concrete sample.

2.2.4 TEMPERATURE DEVELOPMENT IN CONCRETE

The temperature development in concrete, due to the heat of cement hydration, was measured at the center of a 30013001300 mm concrete block, completely encapsulated by 50-mm thick polystyrene foam. The history of the temperature in the block was monitored over 3 days. It was started immediately after casting the concrete, about 20 minutes after the addition of the water to the concrete mix. The ambient temperature in the laboratory was also recorded every 15 minutes, over the same period.

2.2.5 COMPRESSIVE STRENGTH

The compressive strength of concrete at a specified age was determined according to AS 1012, Part 9 by testing two 100-mm diameter cylinders. The cylinder specimens were moist-cured in moulds for 1 day followed by continuous curing in lime-saturated water at 23 °C until the age of testing at 3, 28 and 91 days respectively.

2.2.6 ASTM C1202 RAPID CHLORIDE PERMEABILITY TEST

The rapid chloride permeability test was carried out according to ASTM C1202, which was derived from and equivalent to AASHTO T-277 method. In this program, tests were carried out at the ages of 28 and 182 days for all the nine concrete mixes. Concrete cylinders of 100-mm diameter were cast for the preparation of test specimens and cured in lime-saturated water until two days before the age of testing. Then, two test specimens of 50-mm thickness were saw cut from cylinders and the procedures in ASTM C1202 were followed to pre-condition the specimens until the day of testing. The test result of a concrete mix at a testing age is indicated in coulomb units, which is the average of electrical charges passing through two specimens over the six-hour test period.

2.2.7 STATIC PONDING IN 3% NaCl SOLUTION OVER 91 DAYS

This test was developed at the BRC specifically for this research program, based on the chloride concentration (3% NaCl) and ponding duration (90 days) of the standard static ponding test AASHTO T-259. However, instead of analysing the acid-soluble chloride content of a concrete specimen at different depths, the depth of water-soluble chloride-ion penetration is determined by spraying 0.1 M $AgNO_3$ solution onto the broken specimen section. This procedure greatly reduces the cost of the test and makes it a very simple one to carry out.

After spraying the $AgNO_3$ solution onto a broken specimen section, a colour change within the chloride penetrated depth becomes visible due to the reactions of the soluble chloride ions with the silver nitrate, which forms a white precipitate of silver chloride. According to a previous research work (Otsuki et al, 1992), the 0.1 M $AgNO_3$ solution will detect the water-soluble chloride-ion concentration down to 0.15% by weight of cement. It is also noted that, in the American concrete standard ACI 318, the water-soluble chlorides of 0.15% by weight of cement have been chosen as the maximum limit of chloride-ion content in reinforced concrete.

Two 10011001200 mm prism specimens were cast for each concrete mix. They were moist cured in moulds for one day, then lime-saturated water cured until the age of 7 days. Between 7 to 28 days, they were air cured in a temperature controlled room at 23 °C.

From the age of 28 days, the specimens were immersed in 3% NaCl solution with the struck (trowelled) surface to the side. The salt solution was about 50 mm over the specimens and was regularly monitored and replaced.

At the end of 91 days immersion, the specimens were broken perpendicularly across the middle section and sprayed with 0.1M $AgNO_3$ solution on the broken surfaces. The chloride penetration depth on a broken section was measured from the trowelled surface at the center and two quarter-points. The average of six readings from each pair of specimens, was taken as the chloride penetration depth of the concrete mix.

2.2.8 STATIC PONDING IN 15% NaCl SOLUTION

This test was developed at the BRC for the purpose of accelerating chloride penetration and reducing the test duration, by using a higher concentration of NaCl in the test solution. This test was also used to compare the test results of static ponding to that of cyclic ponding (described in section 2.2.9). In this research program, this test was carried out on all the nine mixes over the ponding duration of 14 days, commenced at the age of 28 and 182 days.

The specimens and the curing conditions were the same as that in the 91days 3% NaCl ponding test (section 2.2.7). The specimens were moist cured in moulds for one day, then lime-saturated water cured until the age of 7 days. Afterwards, they were air cured in a temperature controlled room until testing at the age of 28 and 182 days.

From the age of 28 and 182 days, two specimens were immersed in 15% NaCl solution with the struck (trowelled) surface to the side. At the end of 14 days immersion, the specimens were broken perpendicularly across the middle and sprayed with 0.1M $AgNO_3$ solution, to determine the chloride penetration depth, as described in section 2.2.7.

2.2.9 CYCLIC PONDING IN 15% NaCl SOLUTION

This test has been developed and used at the BRC for some years. The basis of the test is that salt-water ponding with cyclic wetting and drying provides conditions, which closely simulate those of the splash zone or tidal zone in marine environments. During the wetting period, salt-water penetrates into the concrete by capillary action. During the drying period, water is drawn out of the concrete as vapour, leaving the salt in the matrix. This results in an accumulation and a higher concentration of chlorides, as well as the acceleration of chloride penetration into the concrete. It has been found that the cyclic chloride ponding procedure accelerates chloride penetration, compared to static ponding over the same test duration with 5% NaCl test solution. The use of 15% NaCl solution in the test resulted in a further acceleration in the chloride penetration depth when compared to the use of 2% or 5% NaCl solution (Chang and Marosszeky, 1997, ACI SP-170).

The cyclic ponding test procedure consists of cycles of 12-hours of immersion in 15% NaCl solution at room temperature and 12-hours drying at about 40 1C (achieved with heating lamps). In this program, this test was carried out on all the nine mixes for the duration of 14 days, commencing at the age of 28 and 182 days.

The specimens and curing conditions were the same as those in the above static ponding tests (section 2.2.7). The specimens were moist cured in moulds for one day, then lime-saturated water cured until the age of 7 days. Afterwards, they were air cured in a temperature controlled room at 23 °C until testing at the age of 28 and182 days.

At the testing ages, the specimens were placed in the cyclic testing basin with the struck (trowelled) surface to the side and subjected to timer controlled cycles, for the duration of the test. At the end of each test, two specimens were broken perpendicularly across the middle and sprayed with 0.1M $AgNO_3$ solution to determine the chloride penetration depth as described in section 2.2.7.

2.2.10 WATER ABSORPTION

The water absorption test in this program was based on ASTM C642 with modified pre-conditioning procedures. ASTM C642 requires the specimens to be oven-dried at 100 to 110 °C to a constant weight before being immersed in water. There was, however, a concern that this oven-dry procedure may have different effects on the various binary binder systems. It was then adopted to precondition the specimens, after an initial 7 days lime-water curing, at 23 °C and 55±10% R.H. until the time of immersion at the age of 28 days.

The specimens were of the same size and were prepared in the same way as those in the above chloride ponding tests (section 2.2.7).

At the age of 28 days, the specimens were cleaned with a dry brush to remove any dirt and loose particles and were weighed to the nearest 0.01g (W1). They were then immersed in a water tank with the struck (trowelled) surface sideways, supported at the third-points along their length. The water level was about 50 mm over the specimens and water was regularly replaced.

After 72 ±1 hours of immersion, the specimens were removed from the water tank and weighed in a saturated surface dry condition (W2). The air-dry water absorption was then determined by the difference of W2 and W1 divided by W1 and indicated in percentage.

However, it was found in the BRC binary concrete investigation that the measured air-dry water absorption values were very low and the results had poor correlations with the chloride penetration tests. It was considered that a much higher and varied moisture content in the specimens after air-drying could be responsible for these results.

Therefore, in this ternary concrete investigation, it was decided to compare the oven-dry water absorption results with the air-dry water absorption results. After the air-dry water absorption at 28 days was measured, the specimens were put in an oven at 105 °C over three days and their over-dry weights were measured. The Oven-dry water absorption was then determined by the difference of the oven-dry weight (W3) and the SSD weight (W2) of a specimen divided by W2 and expressed in percentage.

2.2.11 CARBONATION

The carbonation test was an accelerated test with a high concentration of carbon dioxide. A compressed gas cylinder with 12% carbon dioxide (CO_2) was the CO_2 source for the exposure chamber. The gas mixture containing CO_2 was injected into the chamber and monitored with an electronic CO_2 tester until the concentration of CO_2 in the chamber was 10 to 11%. The chamber was then sealed with the specimens inside. After 1 or 3 days, depending to the number of specimens inside the chamber, the CO_2 concentration in the chamber dropped to about 6% and the chamber was refilled to 10 to 11% of CO_2 concentration again. The average of the CO_2 concentration was approximately 8% over the specimen exposure period. The relative humidity in the exposure chamber was maintained between 50 and 70% by adjusting the amount of silica gel put into the chamber.

In this test program, the carbonation depth of the specimens was measured for eight of the nine mixes after 28 and 56 days of exposure. For the testing of each concrete mix, two new 751751150 mm prism specimens were cast. They were moistcured in moulds for one day and then lime-saturated water cured until the age of 7 days. Between 7 to 28 days, they were air cured in a temperature controlled room at 23 ±1 °C and 55 ± 15% RH.

From the age of 28 days, the specimens with the struck (trowelled) surface sideways were placed into a chamber containing an average of 8% CO_2. At the end of 28 or 56 days exposure, two specimens were broken perpendicularly across the middle and sprayed with a 1% phenolphthalein solution to indicate the carbonation depth. The depth was measured from the trowelled surface at the center and the two quarter-points. The average of the six readings from each pair of specimens, was taken as the chloride penetration depth of the concrete mix.

2.2.12 SULPHATE RESISTANCE

Eight of the nine concrete mixes were investigated for their performance in the sulphate resistance test, based on ASTM C1012. A modification was made to the ASTM C1012 procedure by replacing the initial warm water (35 °C) curing with moist curing under 23 °C (see section 2.5 for details of the modification).

It should be noted that this research program commenced before the release of the Australian standard on sulphate resistance test (AS 2350.14-96).

For each test mix four 251251285 mm mortar specimens and ten 50-mm cubes were cast by sieving concrete through 4.74 mm sieves. They were moist cured in moulds for one day and then lime saturated water cured at 23 °C. Twenty-four hours from mixing, two cubes were tested to determine the mortar compressive strength. If the cube strength was less than 20 MPa, then further time was allowed before two more cubes would be tested. This process continued until the cube strength of 20 MPa was achieved.

At the time when cube strength exceeded 20 MPa, the prism specimens were taken out of the curing tank, rinsed and had their initial length measured to the nearest 0.002 mm. The prism specimens were then immersed in a sodium sulphate solution (352 moles of Na_2SO_4 per m^3) and supported by two plastic strips at the third-points along their length.

The length change of the specimens was measured at 1, 2, 3, 4, 8, 13 and 15 weeks after immersion and also at 4, 6, 9 and 12 months. The containers with Na_2SO_4 solution and the specimens were maintained in a temperature controlled room at 23 °C. The Na_2SO_4 solution was regularly replaced; and in order to retain the pH range of the solution between 6 to 8 diluted sulphuric acid was frequently added .

2.3 MATERIALS AND CONCRETE MIX DESIGN

The materials used for the concrete mixes in this investigation are based on local sources and satisfy the requirements of relative Australian Standards. These materials are also widely used in local concrete construction by major cement and concrete suppliers.

2.3.1 BINDERS

2.3.1.1 Ordinary Portland Cement (Type GP)

The ordinary portland cement used is Goliath portland cement (Type GP) supplied by Australian Cement Ltd. The typical chemical composition of the Goliath Type GP cement is shown in the following Table 2.3-1. The typical fineness index of the Goliath Type GP cement is 350 m^2/kg.

Table 2.3-1 Chemical Compositions of Cements and SCMs

Element	Chemical Composition (%)				
	Type GP Cement	35% Slag Blended Cement	65% Slag Blended Cement	Silica Fume	Fly Ash (low calcium)
CaO	64.3	55.9	49.9	----	1.35
SiO_2	20.0	24.7	28.2	93.1	64.3
Al_2O_3	4.6	7.9	10.0	----	24.4
Fe_2O_3	3.8	2.8	1.9	----	3.51
SO_3	2.6	3.0	2.7	0.03	----
MgO	1.8	2.7	3.4	----	0.66
K_2O	0.6	0.4	0.2	----	1.64
L.O.I.	2.7	1.6	0.7	4.8	1.23

2.3.1.2 Slag Blended Cement

Two slag blended cements (35% slag blend and 65% slag blend) used in the project were supplied by Australian Cement Ltd. The chemical composition of these two slag blends is also shown in Table 2.3-1. The typical fineness indices of the 35% and 65% slag blend are 380 m^2/kg and 410 m^2/kg respectively.

2.3.1.3 Silica Fume

The silica fume used in this project is Micropoz supplied by CSR Readmix. The chemical composition of the silica fume, identified as Type U by Microsilica JV Pty. Ltd., is shown in the Table 2.3-1. The fineness of the silica fume is indicated by 95.6% of particles passing through a 45 μm sieve.

2.3.1.4 Fly Ash

The fly ash used in this project is fine grade, supplied by Australian Cement Ltd. from Eraring Power Station through Fly Ash Australia Pty. Ltd. The chemical composition of the fly ash is shown in the Table 2.3-1. The fineness of the fly ash is indicated by 84.1% of particles passing through a 45 μm sieve.

2.3.2 COARSE AND FINE AGGREGATES

The coarse aggregates used in this project were 20/14 mm and 10/7 mm crushed river gravels. The fine aggregates used were a coarse river sand and a fine concrete sand.

The coarse aggregates and the coarse sand were Nepean River gravel and river sand, supplied by CSR Readmix. The fine sand was a fine concrete sand supplied from Rocla Relcrete. There was some concern about the performance of the alkali aggregate reaction (ASR) from the Nepean source. Therefore, the supplier (CSR readymix) was required to submit a test certificate to confirm the suitability of the aggregates. The CSIRO test was carried out using a combination of the aggregates and Goliath cement for ASR evaluation. The test certificate issued by CSIRO indicated that the expansion was below 0.10% at 21 days of the accelerated testing. The test results satisfied the relevant RTA B80 requirements.

2.3.3 WATER REDUCER AND SUPERPLASTICISER

The chemical admixtures used are MBT products, a water reducer Pozzolith 370 and a compatible superplasticiser Rheobuild 1000. The Pozzolith is a modified salt of lignosulphonic acid and is of a normal setting type. The Rheobuild 1000 is a calcium salt of naphthalene formaldehyde condensate and is also of a normal setting type.

2.3.4 CONCRETE MIX DESIGN

Sieve analyses and specific gravity analyses were carried out for all the coarse and fine aggregates. The specific gravity of each aggregate was determined under the saturated surface dry (SSD) condition. Based on the results of the aggregate analyses, a basic concrete mix with a binder content of 500 kg/m^3 and w/b ratio of 0.35 was designed using the conventional mix design method. The method originated from the Road Note No. 4 on Design of Concrete Mixes (Road Research, London). Table 2.3.4-1 gives the basic mix design spread sheet and Fig 2.3.4-1 shows the grading curve (denoted as HPC-3 mix) for the mix design. The Coarse and Fine grading curves in Fig 2.3.4-1 represent the boundaries of the recommended range of particle grading from the Road Note No. 4.

The proportions of all the concrete mixes in this program were adjusted from the basic mix design by a simplified procedure based on the proportional change of the aggregate quantities to compensate for the change in binder content and water content. This simplified procedure resulted in some variation in the yield, which varied in the range of 0.994 to 1.027 cubic metres from the nominal one cubic metre for all the nine mixes. However, the w/b ratio of a mix was not affected and the influence of the yield on the binder content was not significant. Overall, the variation of the actual binder content to the nominal binder content was in the range of +0.6% to –2.6% percent for all the mixes.

2.4 MIXING CONCRETES AND CASTING SPECIMENS

The concretes were mixed in a 0.25 cubic-meter pan mixer. Before batching each mix, the estimated amount of the required coarse and fine aggregates were taken from the bulk and stored in covered containers. The moisture content of the aggregates was analysed by weighing samples before and after they were ovendried at 105 °C. The difference between the moisture content of the aggregates under SSD condition and in storage was taken into consideration when batching the aggregates and adding water.

The materials were loaded into the mixer so that the cementitious materials were sandwiched between the aggregates. In most cases, some amount of water-reducer (about half of the maximum dosage of 400-ml per 100-kg binder content) was mixed into the water of the batch. After the initial addition of the batch water with the mixed water reducer, any further additions of water reducer and/or superplasticizer was determined by the consistency of the concrete being mixed.

The first slump was measured about 3 to 4 minutes after the addition of water to the batch. If this slump was still lower than the target slump of 80 ± 20 mm, then more water reducer or superplasticizer was gradually added until consecutive measurements of slump fell into the target range.

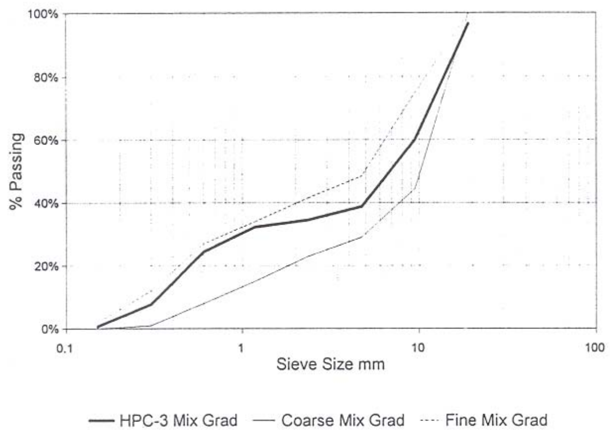
Table 2.3.4-1 Typical Mix Design for HPC-3 Concretes

OPC Concrete Mix : M24 w/c= **0.35**

	Fine Sanc	C/Sand	10 mm	20 mm	Mix	Cement	Water	Total
SSD weigh(kg)	**136**	**455**	**409**	**746**	**1746**	**500**	**175**	**2421** (kg)
Vol (m^3)								**1.00** (m^3)
Sieve size mm	Passing %	Passing %	Passing %	Passing %	Passing % (Cumulat)	Each Size Fraction %	Retained % (Cumulative)	
19	100.00%	100.00%	100.00%	92.05%	96.60%	3.40%	3.40%	
9.5	100.00%	100.00%	89.00%	12.55%	60.06%	36.54%	39.94%	
4.75	100.00%	99.90%	11.85%	4.90%	38.69%	21.37%	61.31%	
2.36	100.00%	97.90%	5.00%	0.00%	34.47%	4.22%	65.53%	
1.18	100.00%	93.90%	0.00%	0.00%	32.26%	2.21%	67.74%	
0.60	96.25%	64.95%	0.00%	0.00%	24.42%	7.84%	75.58%	
0.30	52.15%	13.90%	0.00%	0.00%	7.68%	16.74%	92.32%	
0.15	2.90%	2.15%	0.00%	0.00%	0.79%	6.90%	99.21%	
Base	0.00%	0.00%	0.00%	0.00%	0.00%	0.79%		
	(Zone 4)	(Zone 3)				100.0%		
Fine/Modulus =	1.49	2.27	Total/S=	2.09				

Total F/A= 591 Tota C/A= 1155 Ratio of (CA)/(FA)= 1.95

Fig2.3.4-1 Grading Curve of HPC-3 Mix



In general, the concrete specimens were cast in moulds in two layers of concrete and compacted with a 20-mm diameter poker vibrator. For making the setting time and sulphate resistance specimens, a vibrating table was used, both for sieving mortar out of the concrete and for compacting of the mortar specimens.

After the specimens were cast and surface-finished, plywood sheets were placed above them and they were covered with wet hessian and plastic sheets. The specimens were left in the storeroom at the controlled temperature of 23 °C until the age of 24 ±1 hours, before being demoulded and immersed in lime-saturated water for the specified periods of curing.

2.5 CURING OF TEST SPECIMENS

The details regarding the curing regimes for the test specimens were discussed in the Steering Committee meetings. In principle it was agreed that, for standard tests, the specimens should be cured in accordance with the standards while for non-standard tests, the specimens should be cured in lime-saturated water for 7 days and then air-cured until testing.

Two modifications were also agreed for the curing of the specimens in the ASTM 1012 sulphate resistance test and on the pre-conditioning of the specimens in the ASTM C642 water absorption test. The ASTM C1012 procedure of 24-hour warm-water (35 °C) curing immediately after specimen casting was replaced by moist curing under 23 °C. This modification was requested due to the difficulty involved in sealing the moulds to make them watertight for the warm water curing procedure. The Steering Committee also recommended that the specimens for the water absorption test be pre-conditioned in air instead of oven dried, because of the concern about the influence that the oven drying procedure might have on the hydration products in SCM and PC concretes.

The concrete specimens for compressive strength (AS1012, part 9) at 3. 28 and 91 days and those for the rapid chloride permeability test (ASTM C1202) at 28 and 182 days were cured in lime-saturated water until the age of testing.

The concrete prism specimens for static or cyclic chloride ponding tests, water absorption test and carbonation test were cured in lime-saturated water for 7 days then air cured at 23 °C until testing. While the majority of these tests commenced at the concrete age of 28 days, some of the 15% NaCl static and cyclic ponding tests commenced at 182 days.

3. TEST RESULTS AND DISCUSSION

A wide range of test results on both fresh and hardened concretes was obtained from the experimental tests of this investigation. The test results provided comprehensive information for the evaluation of the performance of the ternary and PC concrete mixes, based on the use of local materials. This chapter presents the test results and the discussions of these results.

In general, the concrete mixes in this investigation have relatively high binder contents and low w/b ratios. Therefore, most of the ternary mixes are not comparable with those binary concrete mixes in the parallel BRC binary concrete project. On the basis of the same binder content and w/b ratio, only one ternary mix M-28 was comparable to the two binary concrete mixes M-7 and M-13. The mix M-28 contained 8% SF and 30% FA in its ternary binder, while the mixes M-7 and M-13 had 8% SF and 30% FA in their binary binders. These three mixes had the same binder content of 400 kg/m^3 and w/b ratio of 0.40. Thus, in discussion of the test results of M-28, the results of M-7 and M-13 are quoted and compared in this report.

3.1 WORKABILITY

In this program, the workability of concrete was evaluated by the water demand of a mix to achieve its initial target slump and the slump loss over the first 30 minutes after the initial target slump had been measured.

An initial target slump of 80 ± 20 mm was set for all the concrete batches in this test program. The actual initial slumps achieved for all the nine concretes were in the range of 70 to 100 mm. The maximum dosage of the water reducer (Pozzolith 370) was limited to 400-ml per 100-kg cementitious binder content based on the manufacturer's recommendations. There was no limitation on the superplasticizer dose, if it was needed to achieve the target slump.

The slump test procedures were carried out according to the AS 1012, part 1. During the mixing of concrete, the first slump was measured about 3 to 4 minutes after the addition of water into the batch. If this slump was still lower than the target, more water reducer (up to 400 ml per 100-kg binder content) or superplasticizer was added until the measured slump fell into the target range. This slump is therefore defined as "*initial slump*". Another slump test was carried out 30 minutes after the "initial slump" was measured and called the "*30 min. slump*". The difference between these two slump measurements is defined as the "*slump loss*". Since the "initial slumps" of the concretes were of different values, even within the target range, a "*percentage slump loss*" is defined as the slump loss divided by the initial slump in percentage and written as "***slump loss (%)***" in this report. This made the comparisons between those concretes, which had somewhat different initial slumps, more convenient.

3.1.1 WATER DEMAND

The water demand of a concrete mix was evaluated by the amount of water reducer (WR) and superplasticizer (Super) that was required to achieve the initial slump target. A comparison was made between the ternary concretes and the related control PC concretes with the same binder content and w/b ratio. Table 3.1-1 shows the amount of chemical admixture used for all the nine mixes divided into three groups according to the binder content and water to binder ratio. The ratio of the Super dosage, or water reducer dosage in the case of 500-kg binder mixes, of each ternary mix to that of the PC control mix is also presented in Table 3.1-1.

Table 3.1-1. Amount of Chemical Admixture used in Each Mix

Mix No.	Binder Type	Binder Content (kg/m^3)	W/b Ratio	Water Content (L/m^3)	WR Dosage (ml/100 kg)	Superplasticizer	
						Dosage Rate (ml/100 kg)	Ratio to PC Mix
M 22	**PC**	400	0.40	160	**400**	**269**	**1**
M 28	8%SF+30%FA				400	303	1.13
M 23	**PC**	450	0.35	157.5	**400**	**292**	**1**
M 25	20%FA+50%SG				400	231	0.79
M 29	8%SF+20%FA				400	352	1.21
M 30	8%SF+30%FA				400	416	1.42
M 24	**PC**	500	0.35	175	**295**	**0**	**1**
M 26	20%FA+35%SG				321	0	(1.1)*
M 27	20%FA+50%SG				400	65	(>1.36)**

Note:
* : the ratios in the brackets are ratios of the doses of water reducer
** : additional to the note under '*', Super was used in this mix

Ternary Concrete Type I: PC +8%SF +(20 or 30)%FA

All three concretes of this ternary binder type had a higher water demand than the control PC concretes.

It has been generally acknowledged that compared to PC concrete, silica fume concrete has a higher water demand, while fly ash concrete normally has a lower water demand. This has also been confirmed in the parallel project of this research work on binary binder concretes.

Therefore, the higher water demand of the three ternary concretes appears to be due to an overwhelming effect of silica fume on water demand in these ternary binders. However, the ternary binder with fly ash did reduce the water demand of the binary mix with silica fume.

In the BRC binary concrete investigation, the two binary concretes (M-7 and M-13) are comparable with the ternary mix M-28. All the three mixes have the same binder content

(400 kg/m^3) and w/b ratio (0.40). The ternary mix M-28 contains 8% SF and 30% FA in its binder, while the binary concretes M-7 and M-13 have 8% SF and 30% FA in the binder respectively. While the Super dosage rate of M-7 and M-13 is 523-ml and 75-ml (per 100-kg binder) respectively, the Super dosage rate of the ternary mix M-28 is 303-ml, right in the middle of the other two values. In this case, the water demand of the ternary mix is the average of the two binary mixes.

Comparing the results of M-29 and M-30, both containing 8% SF and 20% or 30% FA respectively, M-30 did not benefit from its 30% FA compared to M-29 which had 20% FA. In fact, M-30 consumed a slightly higher Super quantity than M-29.

In general, the ternary concretes containing both SF and FA in this program had higher water demand than the control PC concretes. This could be due to the overwhelmingly high water demand of the silica fume in the binder. However, ternary concrete containing both SF and FA had a reduced water demand compared to binary concrete which only contained SF.

Ternary Concrete Type II: PC +20%FA +(35 or 50)%Slag

In the BRC binary concrete project, the water demand of slag concretes (35, 50 and 65% slag) was found to be higher than that of PC concretes, except for the mix with 35% slag in the binder (binder of 400 kg/m^3 and w/b of 0.4). The binary slag mix with 50% slag had higher water demand than the mix with 35% slag in the binder.

In this investigation of ternary concretes, the mix M-25 (20%FA +50%Slag) with the binder content of 450 kg/m^3 recorded a lower water demand than the PC control concrete. However, the other two mixes with a binder content of 500 kg/m^3, M-27 (20%FA +50%Slag) had a higher water demand and M-26 (20%FA +35%Slag) had almost the same water demand as the PC mix.

The only difference between M-26 and M-27 was the slag content in the binder, 35% and 50% respectively. In this case and similar to that in the binary slag mixes, the ternary mix with 50% slag content had a higher water demand than the ternary mix with 35% slag in the binder.

3.1.2 SLUMP LOSS OVER 30 MINUTES

Table 3.1-2 and Fig 3.1-1 show the test results of the percentage slump loss for all the nine mixes divided into three groups according to the binder content and w/b ratio. Ratios in the slump loss (%) between a ternary mix and its PC control mix are also presented in Table 3.1-2.

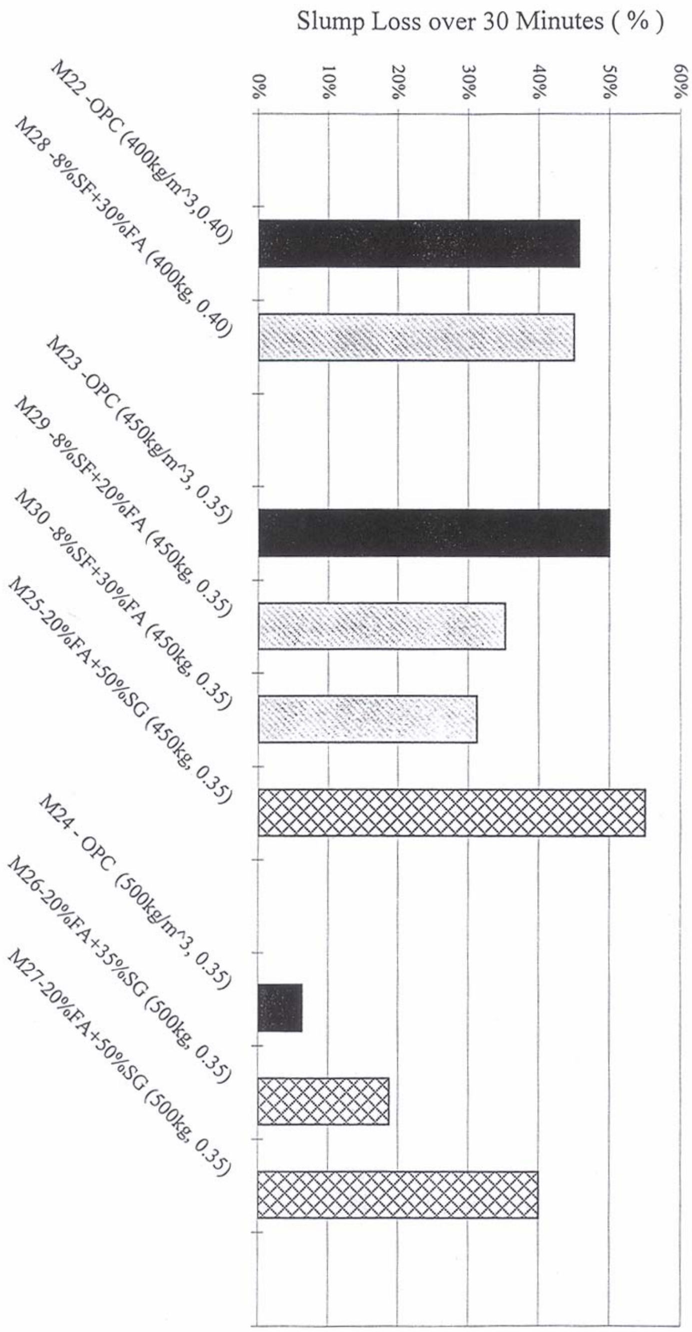


Fig 3.1-1 Slump Loss in Percentage over 30 Minutes

Table 3.1-2. Slump Loss over 30 Minutes in Each Mix

Mix No.	Binder Type	Binder Content (kg/m^3)	W/b Ratio	Water Content (L/m^3)	Initial Slump (mm)	Slump Loss in 30 min.	
						Slump Loss (%)	Ratio to PC Mix
M 22	**PC**	400	0.40	160	**70**	**46**	**1**
M 28	8%SF+30%FA				100	45	0.99
M 23	**PC**	450	0.35	157.5	**90**	**50**	**1**
M 25	20%FA+50%SG				100	55	1.10
M 29	8%SF+20%FA				85	35	0.71
M 30	8%SF+30%FA				80	31	0.63
M 24	**PC**	500	0.35	175	**80**	**6**	**1**
M 26	20%FA+35%SG				80	19	2.98
M 27	20%FA+50%SG				100	40	6.35

Effect of Water Content on Slump Loss

In the BRC binary concrete project, the effects of binder content and w/b ratio were found in a similar manner to the slump loss (%) of the tested concrete. Therefore, their effects can be indicated by a single parameter, the free water content of a mix, which is the product of the binder content and the w/b ratio of the mix. A significant effect of the water content on the slump loss (%) was observed in the PC mixes, the higher the water content the lower is the slump loss (%). For binary concrete mixes, the trend between the water content and slump loss is similar to that in PC concrete but the effect is much less significant.

In this investigation of ternary concretes, similar conclusions can be drawn. For three PC concrete mixes with water content of 157.5, 160 and 175 kg/m^3, the 30-minute slump loss (%) was 50, 45.7 and 6.3 percent respectively. However, because of the additional effects of the SCMs on slump loss, the effect of water content on slump loss of the ternary mixes became less significant, although a similar trend could be found within mixes with the same ternary binder.

Ternary Concrete Type I: PC +8%SF +(20 or 30)%FA

All three mixes of this ternary binder type had lower values of slump loss (%) than the control PC mixes. These results are opposite to that of the water demand, in which these ternary mixes all had a higher water demand than the PC mixes.

As shown in the BRC binary concrete research, a higher water demand does not necessarily mean a high slump loss (%) for SCM mixes, especially for the silica fume mixes.

Comparisons were made between the slump loss (%) of the ternary mix M-28 (8%SF +30%FA) and the two binary mixes, M-7 and M-13, that contained 8% SF and 30% FA respectively. These three mixes had the same binder content (400 kg/m^3) and w/b ratio

(0.40). M-7 (8%SF) had a slump loss of 43.8%, M-13 (30%FA) had 52.6%, while M-28 (8%SF +30%FA) recorded a slump loss of 45.0%. The slump loss of the ternary mix M-28 was between the results of the two binary mixes M-7 and M-13.

The slump loss (%) results of the other two ternary mixes, M-29 and M-30, were very close to each other, and while both contained 8% SF their FA content was 20% and 30% respectively.

In general, ternary concrete containing both SF and FA had a similar or lower slump loss than the control PC concretes. The slump loss performance of such a ternary concrete may be described as a balance of the binary mixes containing SF and FA. The increase of the FA proportion in the ternary binder from 20% to 30% was found to have only a little effect on reducing slump loss over a period of 30-minutes.

Ternary Concrete Type II: PC +20%FA +(35 or 50)%Slag

In the BRC binary concrete project it was found that the slump loss (%) was higher for the slag concrete (with 35, 50 or 65% slag in binder), but lower for the 20% FA concrete, when compared to that of the PC control concrete.

In this investigation of ternary concretes, all the three ternary mixes containing both slag and FA recorded higher slump losses (%) than the PC controls. It appeared that the effect of the slag content, rather than the fly ash content, was overwhelming in these ternary mixes.

M-25 (20%FA +50%Slag) was also found to have higher slump loss than the ternary mixes (M-29 and M-30) containing SF +FA within the group with a binder content of 450 kg/m^3 and w/b of 0.35 (see Fig 3.1-1).

For the two comparable mixes with different slag contents, the mix with the higher slag content, M-27 (20%FA +50%Slag), had a higher slump loss (%) than M-26 (20%FA +35%Slag). Further comparisons of the results to that of the PC mix M-24 indicated that an increase in slump loss was significant with the increase in the slag content in the binder.

Comparing M-25 and M-27 on the effects of binder content and water content, the richer mix M27 had a lower slump loss (%) than M-25. However, when comparisons were made of the two mixes with their respective PC control, M-27 had a higher relative slump loss (%) to the PC mix than M-25.

In general, the ternary mixes containing both SG and FA had a similar or higher slump loss (%) than the control PC mixes or the ternary mixes with both SF and FA in their binders. An increase of the slag content in the ternary mixes with 20% FA resulted in an increase in slump loss (%).

It should be pointed out that the slump loss results were measured under the laboratory condition. Unlike the concrete supplied on site from ready-mix plants, at the laboratory there was no continuous agitation after a concrete batch was mixed and discharged into a wheelbarrow. This difference could result in different slump loss percentages for concrete mixed at the laboratory compared to one that is supplied on site, even if the same mix proportion is used. So, a direct comparison of the laboratory test results to that of ready-mix batches on site may not be appropriate.

3.2 SETTING TIME

The setting time tests were carried out according to the AS 1012, Part 18. Seven out of the nine concrete mixes were tested. There were four ternary mixes, two of each ternary binder type, and three PC mixes. Table 3.2-1 and Fig 3.2-1 present the results of the initial and the final setting time of the six concretes tested. The time-lapse between the initial and the final setting for each mix is also shown in Table 3.2-1.

The initial setting time of a concrete mix is normally considered more important than the final setting time. The initial setting time tells the users how much time is available for mixing, transporting, placing and compacting the concrete, as well as the maximum interval for successive layers without leaving cold joints. Therefore, the initial setting time is more frequently mentioned in the following discussions of the setting time test results.

Table 3.2-1 Setting Time Test Results

Mix No.	**M-22**	**M-28**	**M-23**	**M-30**	**M-24**	**M-26**	**M-27**
Binder Content (kg/m^3)	400		450		500		
Water/Binder Ratio	0.40		0.35		0.35		
Binder Type	PC	8% SF+ 30% FA	PC	8% SF+ 30% FA	PC	20%FA+ 35%SG	20%FA+ 50%SG
Initial Setting Time (h:m)	**6:15**	**9:15**	**7:05**	**7:45**	**5:05**	**9:25**	**11:00**
Ratio to PC Mix	1	1.48	1	1.09	1	1.85	2.16
Delay Time to PC Mix	0	3:00	0	0:40	0	4:20	5:55
Final Setting Time (h:m)	**7:15**	**10:40**	**8:10**	**9:00**	**6:05**	**11:15**	**13:15**
Ratio to PC Mix	1	1.47	1	1.10	1	1.85	2.18
Delay Time to PC Mix	0	3:25	0	0:50	0	5:10	7:10
Between Initial and Final Set	**1:00**	**1:25**	**1:05**	**1:15**	**1:00**	**1:50**	**2:15**

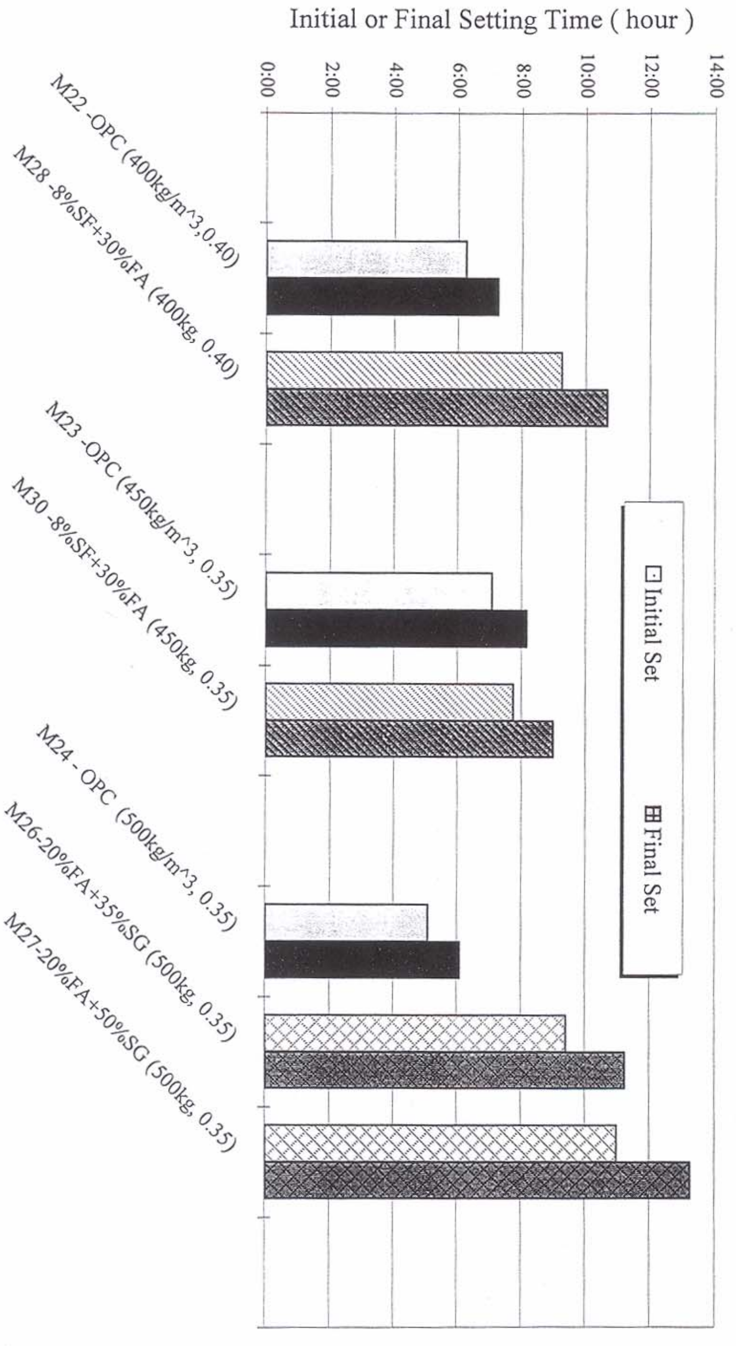


Fig 3.2-1 Initial and Final Setting Time

PC Concrete

The PC concrete mixes M-23 and M-24 had the same w/c ratio of 0.35 but different cement content of 450 and 500 kg/m^3. The initial setting time of the richer mix M-24 was two hours earlier than that of the leaner mix M-23. This observation is consistent with those acknowledged by other investigators. It was also observed that the time lapse between the initial and final setting was nearly the same for both PC mixes, 65 and 60 minutes respectively.

Ternary Concrete Type I: PC +8%SF +30%FA

Both ternary mixes of this binder type had significant delays in both the initial and final setting times compared to the control PC mixes. M-28 recorded the initial setting time of 9h.15m (555 minutes) which was a three-hour delay compared to that of the PC mix M-22. M-30 had a shorter initial setting time of 7h.45m (465 minutes) and only a 40 minutes delay in the initial set compared to the PC mix M-23. The much shorter delay in the initial set of M-30 could be due mostly to the effects of a higher binder content and a lower w/b ratio than that of M-28. The time lapses between the initial and final set for M-30 and M-28 were, however, found to be only 10 and 25 minutes longer than that of their PC control mixes.

It has been shown in the BRC binary concrete investigation that a mass-by-mass replacement of PC with any of the three SCMs (SF, FA and Slag) resulted in delaying the setting time of the concrete.

Comparisons were made between the setting times of the ternary mix M-28 (8%SF +30%FA) and the three binary mixes, M-7, M-12 and M-14 based on the same binder content (400 kg/m^3) and w/b ratio (0.40). M-7 contained 8% SF in the binder and recorded a delay in the initial set of 42 minutes compared to the PC control mix. M-12 and M-14 contained 20% and 40% FA and had a delay in the initial set of 116 and 140 minutes respectively. While direct test results were not available, the delay in the initial set of the binary mix with 30%FA could be assumed as the average of the binary mixes with 20% and 40%FA. The average delay in the initial set of M-12 (20%FA) and M-14 (40%FA) was 128 minutes. The sum of the delays in initial set of the binary mixes with 8%SF (42 minutes) and 30%FA (128 minutes) was 170 minutes, which is close to the delay in the initial set of the ternary mix M-28. However, the time lapse between the initial and final set of the ternary mix M-28 (85 minutes) was only slightly longer than that of the binary SF mix M-7 (81 minutes), but shorter than that of the binary FA mixes M-12 (98 minutes) and M-14 (106 minutes).

In general, two ternary concrete mixes (M-28 and M-30) containing 8%SF and 30%FA in the binder both had longer initial and final setting times than the control PC concretes. The delay in the initial set of the ternary mix (M-30) with a higher binder content and a lower w/b ratio was much shorter than that of M-28. The time lapses between the initial and final set for both ternary mixes were only slightly longer than that of the PC control mixes. The ternary mix M-28 was also found to have longer setting times than the binary mixes containing 8% SF, 20% FA and 40% FA. The delay in the initial set of M-28 would be close to the sum of the binary mixes with 8%SF and 30%FA.

Ternary Concrete Type II: PC +20%FA +(35 or 50)%Slag

In the BRC binary concrete project it was found that the mixes containing fly ash or slag in the binary binder all had longer setting times than the PC control concrete (400 kg/m^3 and w/b of 0.40). The delays in the initial set of these binary mixes were in a range between 95 to 227 minutes when compared to the PC control.

In this investigation of ternary concrete mixes, the two ternary mixes containing 20%FA plus either 35%Slag (M-26) or 50%Slag (M-27) both recorded much longer setting times than the PC control mix of the same binder content (500 kg/m^3) and w/b ratio (0.35). While the PC mix had the initial setting time of 5h.05m (305 minutes), the ternary mixes M-26 and M-27 recorded initial setting times of 9h.25m (565 minutes) and 11h.00m (660 minutes) respectively. The delay in the initial set was 260 minutes for M-26 and 355minutes for M-27 when compared to the PC mix M-24. The time lapses between the initial and final set of the two ternary mixes were 110 minutes and 135 minutes, both of which were significantly longer than the 60 minutes of the PC mix.

In summary, the ternary mixes containing both Slag and FA had much longer initial and final setting times than the control PC mix. The increase of slag content from 35% to 50% in the ternary binders with 20% FA resulted in further increase of both setting times.

Further Discussion

In general, the initial and final setting times of ordinary portland cement concrete are directly related to the water to cement ratio and inversely related to the cement content. Other important factors that influence the time of setting include types of cement, fineness of cement, temperature, and types of chemical admixtures used.

With the incorporation of SCMs, a general agreement in the literature is that low-calcium fly ash and slag have some retarding effect on the setting time of concrete, while silica fume up to 10% in the binder has only a slight retarding effect on the setting characteristics of concrete.

The setting time test results in this program were based on the local SCM materials and they were also generally consistent with the work of other researchers in North America.

The chemical admixtures were not set as variables to be investigated in the setting time test. Since the need to achieve the same target slump was a priority, the dose of water reducer or superplasticizer was different for each of the seven mixes. . Therefore the effects of the chemical admixtures on the setting time of the SCM concretes needs to be further investigated with the chemical admixture dosage as an isolated variable.

The standard AS 3972 on “Portland and Blended Cements” requires a minimum setting time of 45 minutes and a maximum setting time of 10 hours for both types of cements tested by AS 2350.4. However, this requirement is based on testing cement paste by the Vicat needle test and therefore is not applicable to concrete.

The setting time of concrete made from mortar sieved from concrete is different to that of cement paste. Usually, the setting time of concrete is much longer than that of cement paste. Since the setting time of concrete can also be influenced by such other factors, as ambient and concrete temperature and wind velocity, the setting times of field concretes can also differ from that determined in laboratory tests.

There are no specific limitations on the setting time for concrete, in fact, the ideal setting time for a concrete mix can vary from several hours to longer than a day, depending on the demands of different applications. For example, in the construction of the foundations of a bridge in Japan (Kashima et. al, 1992), an initial setting time of about 30 hours was needed, to allow the continuous placing of large quantities of concrete and to obtain the required quality.

In general, the test results indicated that ternary concretes based on equal-mass replacement of PC with two SCMs resulted in significant delays in the setting times, especially for those with high proportions of fly ash and slag in the ternary binder. The use of ternary concretes with both FA and Slag may then be beneficial in the continuous placement of large quantities of concrete. They also have the advantage of achieving good concrete quality and integrity. A wide range of setting times required for different field applications can also be achieved with appropriately designed ternary concrete mixes. However, in those cases where a shorter setting time is preferred, care must be taken in proportioning the concretes containing SCMs and appropriate chemical admixtures may also need to be used. It must also be noted that the setting time results in this investigation were obtained under the laboratory conditions. In field, the setting of concrete may be significantly affected by field conditions such as the concrete temperature and the ambient temperature.

3.3 BLEEDING

The bleeding test was carried out according to the AS 1012, Part 6 on the same seven concrete mixes described in the setting time test. Table 3.3-1 and Fig 3.3-1 show the bleeding test results as the ratio of bleed to free water content in a mix. The volume of bleed per unit surface area in the test is also calculated and shown in Table 3.3-1.

PC Concrete

The PC concrete mixes M-23 and M-24 had the same w/c ratio of 0.35 but a different cement content of 450 and 500 kg/m^3. The ratio of bleed of the richer mix M-24 was 1.49%, which is higher than the 1.27% of the leaner mix M-23. This observation is consistent with the generally acknowledged fact that a higher cement content results in a higher water content under the same w/c ratio; thus increasing the bleeding capacity of concrete.

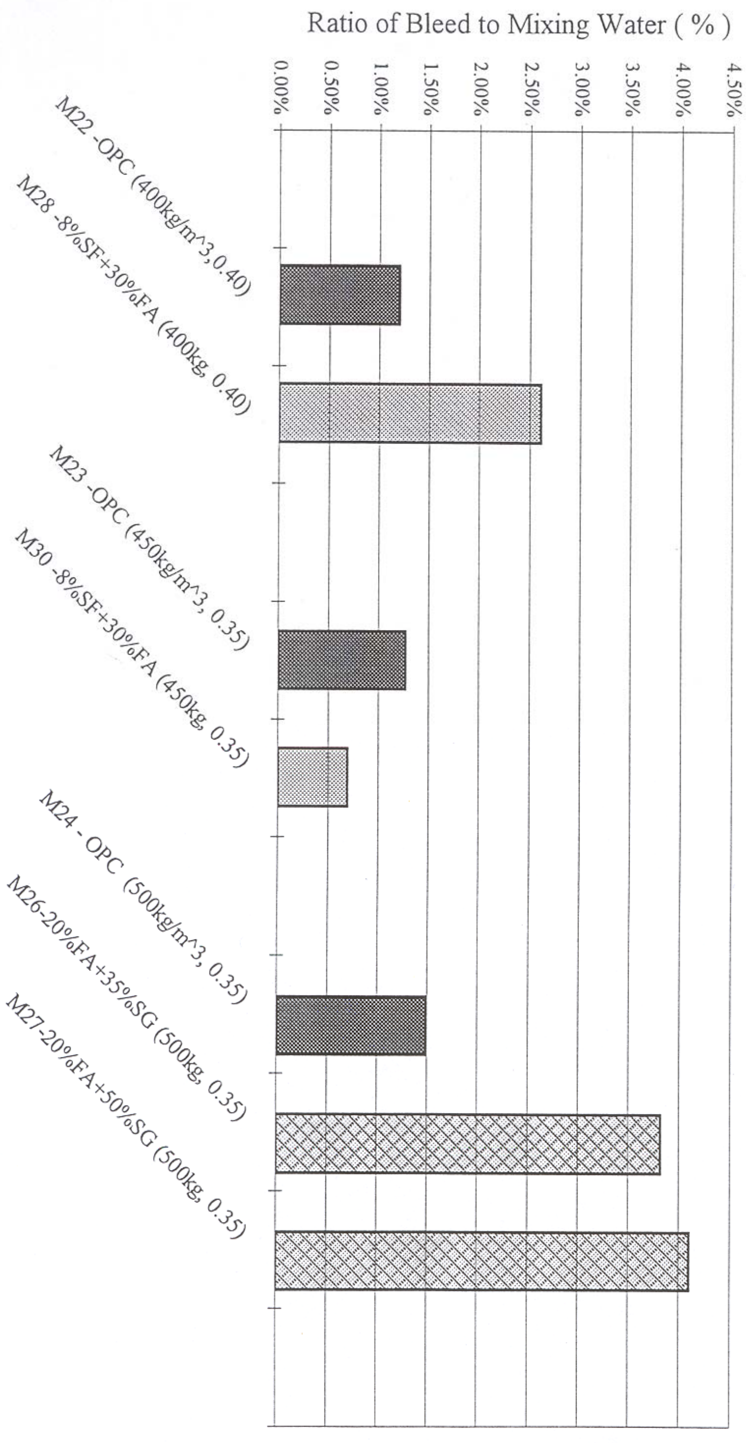


Fig 3.3-1 Ratio of Bleed to Total Mixing Water

Table 3.3-1 Bleeding Test Results

Mix No.	**M-22**	**M-28**	**M-23**	**M-30**	**M-24**	**M-26**	**M-27**
Binder Content (kg/m^3)	400		450		500		
Water/Binder Ratio	0.40		0.35		0.35		
Binder Type	PC	8% SF+ 30% FA	PC	8% SF+ 30% FA	PC	20%FA+ 35%SG	20%FA+ 50%SG
Ratio of Bleed (%)	**1.20**	**2.61**	**1.27**	**0.69**	**1.49**	**3.82**	**4.10**
Ratio to PC Mix	1	2.18	1	0.54	1	2.56	2.75
Vol./Surface Area (ml/cm^2)	**0.050**	**0.104**	**0.051**	**0.027**	**0.065**	**0.166**	**0.179**
Ratio to PC Mix	1	2.17	1	0.54	1	2.55	2.76

A bleed of 1.20% was recorded for the third PC mix M-22, which had a lower cement content (400kg/m^3) and a higher w/c ratio (0.40) than the M-23 mix. Although M-22 did have a slightly higher water content (160 kg/m^3) than M-23 (157.5 kg/m^3), the bleed of M-22 was slightly lower. In this case, it appeared that the effect of w/c ratio was more significant than that of cement content on the bleed of the concrete.

Ternary Concrete Type I: PC +8%SF +30%FA

In the BRC binary concrete investigation, bleed was found to decreased in the binary mix containing 8% silica fume and increased significantly in the binary mixes containing 20% or 40% of fly ash, when compared to that of the PC control mix.

In this investigation of the ternary mixes containing 8%SF and 30%FA, M-28 (400 kg/m^3, w/b of 0.40) had the bleed ratio of 2.61% which was 2.18 times that (1.20%) of the PC mix M-22. On the other hand, the ternary mix M-30 (450 kg/m^3, w/b of 0.35) recorded a bleed of 0.69%, being only 0.54 times that (1.27%) of the PC mix M-23. While the bleeds of the two PC mixes, M-22 and M-23, were of little difference (1.20% and 1.27%), the bleeds of the two ternary mixes, M-28 and M-30, were quite different (2.61% and 0.69%). It appeared that a lower w/b ratio might have a more significant effect on the reduction of bleed of the ternary mixes than on that of the PC mixes.

The bleed value of 2.61% of the ternary mix M-28 (8%SF +30%FA) was also compared to that of three binary mixes, (M-7, M-12 and M-14) based on the same binder content (400 kg/m^3) and w/b ratio (0.40). While M-7 with 8% SF in the binder recorded a bleed of 0.72%, M12 and M-14 containing 20% and 40% FA had bleeds of 4.14% and 3.58% respectively. These results indicated that a ternary mix containing both SF and FA had a balanced bleed capacity between that of the binary mixes with SF and FA respectively.

In summary, the two ternary concrete mixes (M-28 and M-30) containing 8%SF and 30%FA in the binder had significantly different bleed performances. The reason for these differences might be that the decrease in w/b ratio had a more significant effect on the reduction of bleed in this type of ternary mixes than in the PC mixes. Further investigations are needed in this area. The ternary mix M-28 containing 8%SF and 30%FA in the binder was also found to have an intermediate bleed value between that of the binary mixes containing 8% SF (M-7) and 20% FA or 40% FA respectively.

Ternary Concrete Type II: PC +20%FA +(35 or 50)%Slag

It has been found in the BRC binary concrete project that, the mixes containing 20%FA, 35%Slag or 50%Slag in the binary binder (400 kg/m^3 and w/b of 0.40) all had significantly higher bleeds than the PC control concrete. The bleed to free water content of these three binary mixes were 4.14%, 2.99% and 2.03% while that of the PC control mix was 1.20%.

In this investigation of ternary concrete mixes, two ternary mixes containing 20%FA plus 35%Slag (M-26) or 50%Slag (M-27) both recorded much higher bleeds than the PC control mix of the same binder content of 500 kg/m^3 and w/b ratio of 0.35. While the PC mix had a bleed of 1.49%, the ternary mixes M-26 and M-27 recorded bleeds of 3.82% and 4.10% respectively.

In summary, the ternary mixes containing both Slag and FA had significantly higher bleeds than the control PC mix. The increase of slag content from 35% to 50% in the ternary binders with 20% FA also resulted in a further increase of bleed.

Further Discussion

The bleed capacity and the bleed rate of PC concrete are considered to be most significantly affected by the ratio of the surface area of the solids to the volume of mixing water. Therefore, increase in the water content or water to cement ratio can increase bleeding, while the increase in the surface area or fineness of cement reduces bleeding. The increase in cement content normally accompanied by a reduction in w/c ratio may also reduce bleeding.

Based on the above principle, the bleeding of a concrete mix in which the PC has been partially replaced by a SCM, would depend mostly on the fineness of the SCM. If it is finer than the replaced PC, then bleeding should be reduced, and vice versa. Since in most cases SCMs are finer than PC, an equal-mass replacement of PC with a SCM in concrete would be expected to reduce concrete bleeding without other changes in the mix design. However, the results of this investigation, of CANMET as well as other research work do not appear to verify this for the different SCMs tested in both the binary and the ternary mixes.

While it is generally acknowledged that the replacement of PC with silica fume results in a reduction of bleeding, the effects of fly ash or slag on the bleeding of binary concrete varied. In deed only very few test results on the bleeding of concrete with ternary binders is available in the literature.

The effects of equal-mass replacement of PC with SCMs on concrete bleeding are discussed in more details in the BRC report on the binary concrete investigation. Several relevant research results from CANMET and other researchers are also quoted and compared with the results of the binary concretes.

The following discussion summarizes the major effects of each of the three SCMs on bleeding and some of the findings in the BRC binary concrete investigation.

Silica Fume Concrete

It has been generally acknowledged that silica fume can greatly reduce the bleeding of concrete. This has been observed in the BRC binary concrete tests based on the equal-mass replacement of PC with SF. The ability of silica fume to reduce bleeding is considered primarily due to its extreme fineness and thus much greater surface area versus weight. Silica fume concretes with low w/b ratio can essentially have no bleed at all. The great reduction in bleed in silica fume concrete may, however, cause problems associated with plastic shrinkage cracking under hot and windy conditions.

Fly Ash Concrete

Surface area determined by air permeability methods, such as the Blaine apparatus, is commonly used in the portland cement industry. These methods are, however, not suitable for very fine particle size and microporous materials. So, the fineness of fly ash is normally determined by sieve analysis and particularly based on the percent by mass passing 45-μm sieve. In AS 3582.1, the grade of fly ash is defined as fine, medium and coarse by the minimum required percent passing 45-μm sieve as 75, 60 and 40 percent respectively.

The fly ash used in this test program is Eraring ash. It is a fine grade ash and has been used in large quantities by the concrete industry. The percentage of particles passing 45-μm sieve of this fly ash is 84.1% based on the analytical data sheet. A typical particle distribution analysis shows that the percentage of particles passing 11.56-μm sieve is 35.1% and the median particle size is 17.6-μm.

The type of GP portland cement used in the program has the Blaine surface area of 350 m^2/kg. A typical particle distribution analysis also shows that the percentage of particles passing 48-μm and 12-μm sieves are 97.4% and 47.7%. The median size of the GP cement is 13.2-μm.

The above data indicates that the fly ash is coarser than the PC used in this investigation. This could be the main reason for the significantly higher bleeding of the binary and ternary concrete mixes containing fly ash compared to that of the PC mixes. However, further investigations of PC and fly ash of similar fineness are needed to identify the effects of other factors, such as, the shape and chemical compositions of fly ashes on the bleeding behaviour of fly ash concrete.

Slag Concrete

The Blaine fineness of the two slag cements is 380 kg/m^2 for the 35% slag blend and 410 kg/m^2 for the 65% slag blend; both are finer than the PC used in the control mix with the fineness of 350 kg/m^2. However, the bleeding of the binary slag mixes using these two slag cements were significantly higher than that of the PC mix, based on the same binder content and w/b ratio. This indicated that the bleeding behaviour of concretes incorporating slag depends not only on the relative fineness of the slag to the PC, but also on other physical or chemical properties of the slag cements. Further research work is needed in this area.

It should be emphasized that the SCM and PC concrete mixes compared in this program were of the same binder content and w/b ratio due to the equal-mass replacement of PC with any SCMs. This is, however, not necessary to be the optimal way in applications of different SCMs in concrete. For example, fly ash was used on many occasions as filler in concrete to effectively reduce bleed. In this case, there was an increase in the total cementitious binder content in the concrete without reduction in PC quantity. In some other cases where the fly ash was used as part of the binder rather than filler, the replacement of PC with fly ash was often based on the equivalent 28-day strength. This also led to an increase in the total binder content and often a lower w/b ratio.

Under the conditions of equal-mass replacement of PC, the fly ash and slag binary and ternary mixes tested in this program were found to have increased bleed compared to the PC control mix. In many of the published test results in the literature, the SCM concretes and PC control concretes had some differences in binder content or w/b ratio. Since more than one major variable was involved in these cases, the misunderstanding of some of the effects of SCM replacement on bleeding may have resulted. Therefore, in this program the tests were specifically designed to have only one major variable in the mixes, so that the effects of the SCM replacement could be identified and directly evaluated.

However, care must be taken when relating the test results of this program to practical applications. In most applications, the incorporation of a SCM in a concrete mix requires an appropriate adjustment to the mix design rather than just a simple mass-to-mass replacement of the PC by SCMs. The bleeding of a SCM concrete mix could also be adjusted to the preferred level by a re-proportioning the concrete mix. What clearly indicated from the results of this research is that, when SCMs are used in concrete, a careful mix re-design is essential, if expected benefits and property specifications are to be achieved.

It must also be noted that the laboratory results on bleeding were measured under the controlled environment and based on a small volume of sample concrete. In field, the actual bleeding performance of concrete may be significantly affected by field conditions such as the concrete and ambient temperatures and the evaporation rate.

3.4 TEMPERATURE DEVELOPMENT IN CONCRETE

The hydration of portland cement is accompanied by the evolution of heat that can cause a significant temperature rise in the concrete, especially in mass concrete. Since the conductivity of concrete is low, a steep temperature gradient within a concrete mass may be established which can result in thermal stresses and possibly thermal cracking as the concrete cools to the ambient condition.

In general, the replacement of PC with slag or fly ash significantly reduces the temperature rise in concrete. The incorporation of silica fume in concrete may, however, result in a steeper initial temperature rise, although the overall temperature rise in later ages may even be lower than that in a reference PC mix.

The temperature history in seven out of the nine concrete mixes was monitored in this investigation. The seven concrete mixes were the same as that in the setting time and bleeding tests.

As described in the section 3.2.4, a 300-mm concrete cubic block was cast and insulated with 50-mm thick polystyrene foam for this study. The temperature at the centre of the concrete block and the ambient temperature in the laboratory were measured every 15 minutes with thermocouples and through a data acquisition system. The monitoring of temperature history started from about 20 minutes after the water was added to the concrete mix, and was maintained for three days.

Comparisons were made between the temperature at the centre of a concrete block and that at 50 mm to the side surface of the block. The measured maximum temperatures were 56.3 °C and 55.6 °C respectively, a difference of less than 2%. Through the insulation of the concrete block, the effects of the ambient conditions on the temperature in the concrete were eliminated. Therefore, the temperature measured in the sample block is similar to that which would be found in a concrete mass.

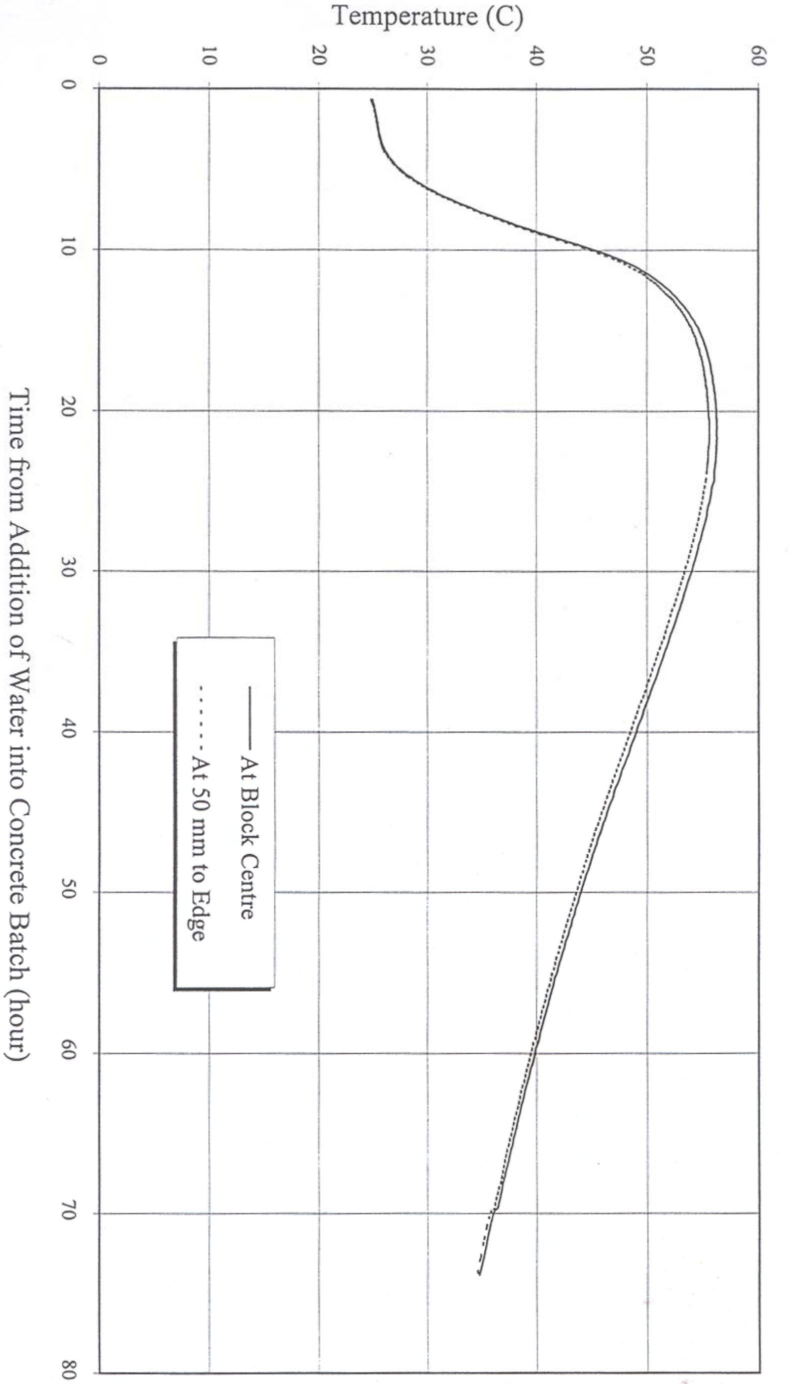
To take into consideration the differences in the ambient temperature when the concrete batches were mixed, the ***maximum temperature rise*** is defined as the difference between the maximum temperature in the concrete block centre and the initial ambient temperature at the time when temperature recording started. It was found that there was little difference between the initial temperature in a concrete block and that in the ambient when the temperature monitoring started (about 20 minutes from adding water).

The results of temperature rises in the seven concrete mixes are compared in Table 3.4-1 and the temperature histories in the seven mixes are presented in Fig 3.4-1 to Fig 3.4-7.

PC Concrete

The PC concrete mixes M-23 and M-24 had the same w/c ratio of 0.35 but different cement content of 450 and 500 kg/m^3. The maximum temperature rise in the richer mix M-24 was 36.7 °C, which is slightly higher than 35.9 °C of the leaner mix M-23. The time lapse, from the addition of water to the mix to the point of the maximum temperature, was also longer for the richer mix M-24 (27 hours) than that for M-23 (23 hours).

Fig 3.4-1 Temperature Development in PC Mix M-22 (400kg/m^3, w/b=0.40)



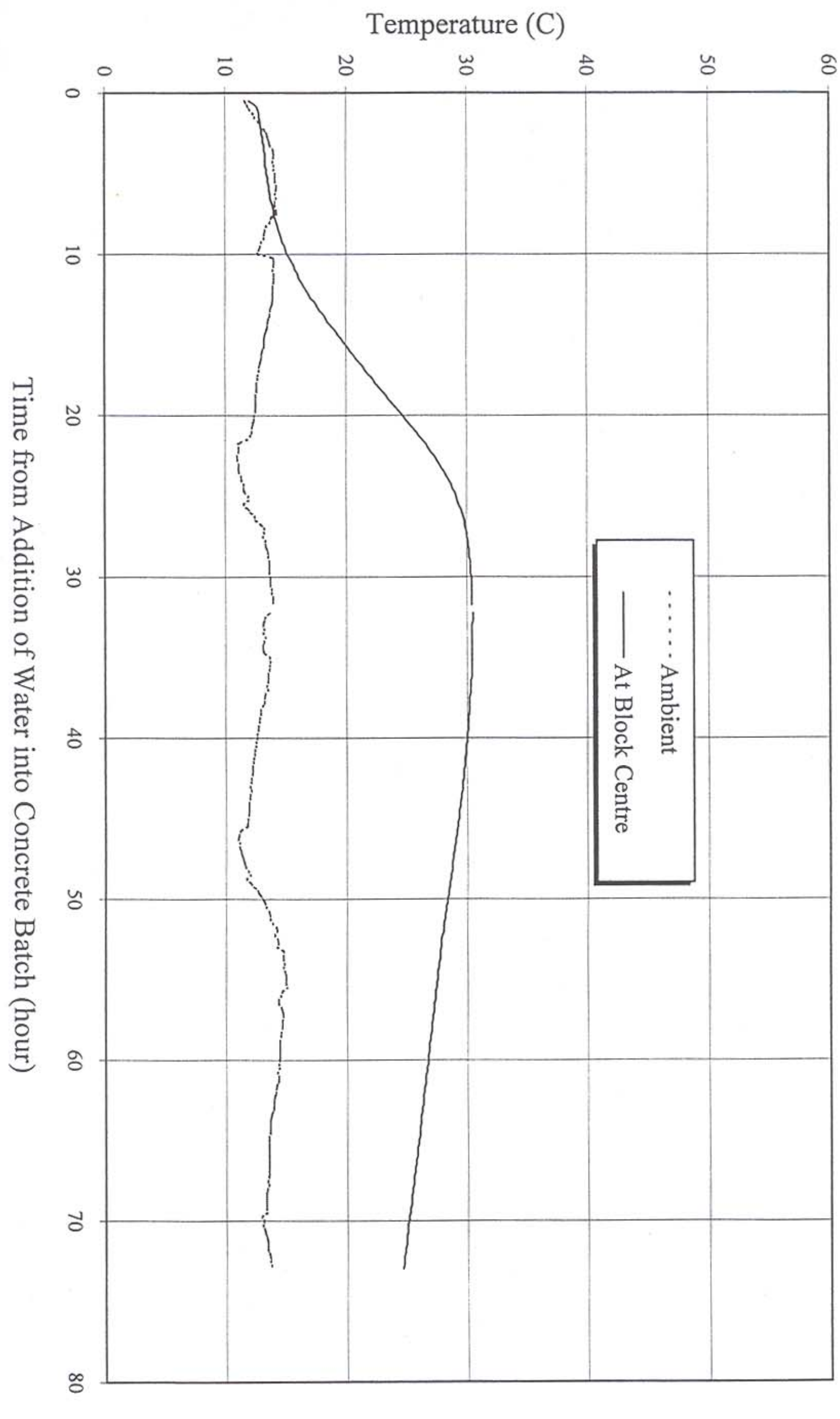


Fig 3.4-2 Temperature Development in M-28, 8%SF+30%FA (400kg/^3, w/b=0.40)

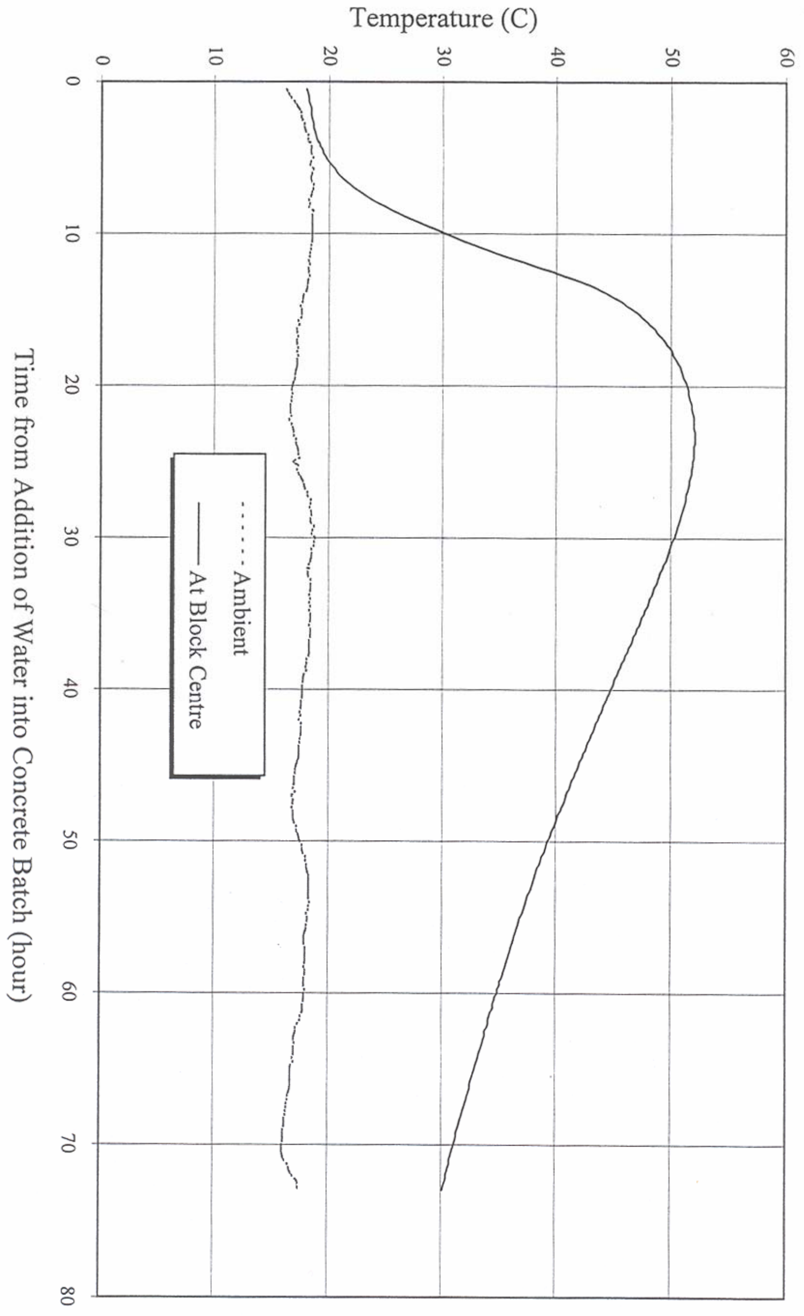


Fig 3.4-3 Temperature Development in PC Mix M-23 (450kg/m^3, w/b=0.35)

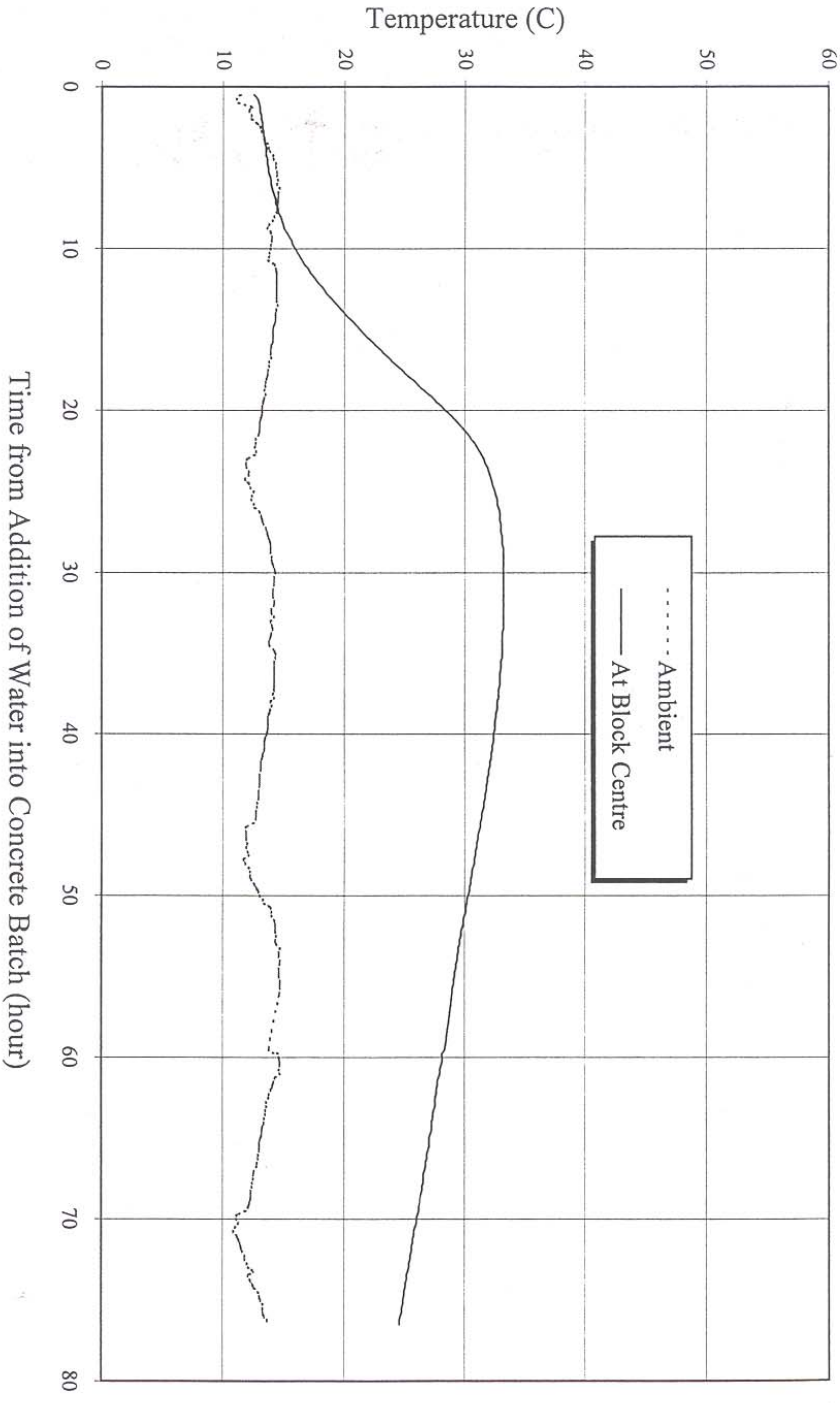


Fig 3.4-4 Temperature Development in M-30, 8%SF+30%FA (450kg/^3, w/b=0.35)

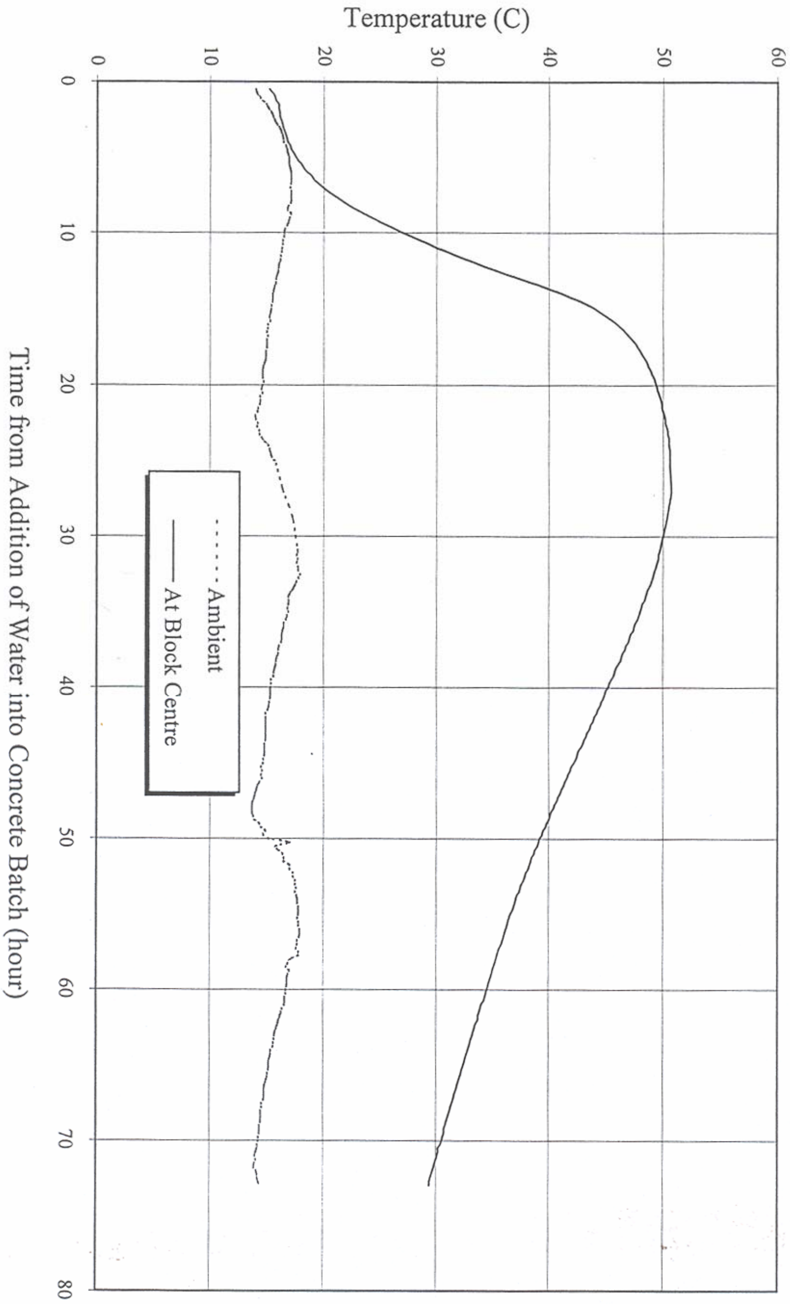


Fig 3.4-5 Temperature Development in PC Mix M-24 (500kg/^3, w/b=0.35)

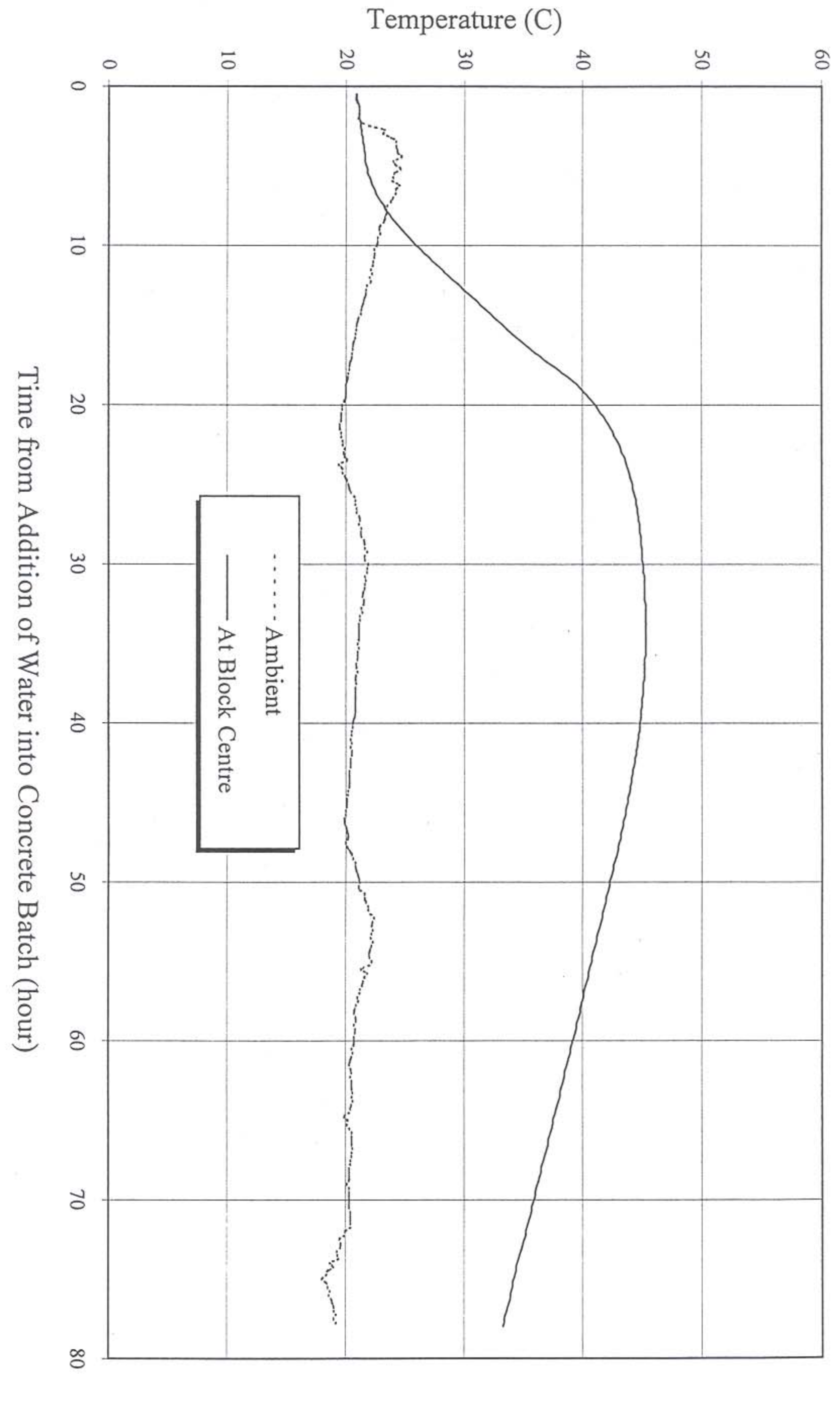


Fig 3.4-6 Temperature Development in M-26, 20%FA+35%SG (500kg/^3,w/b=0.35)

Fig 3.4-7 Temperature Development in M-27, 20%FA+50%SG (500kg/^3,w/b=0.35)

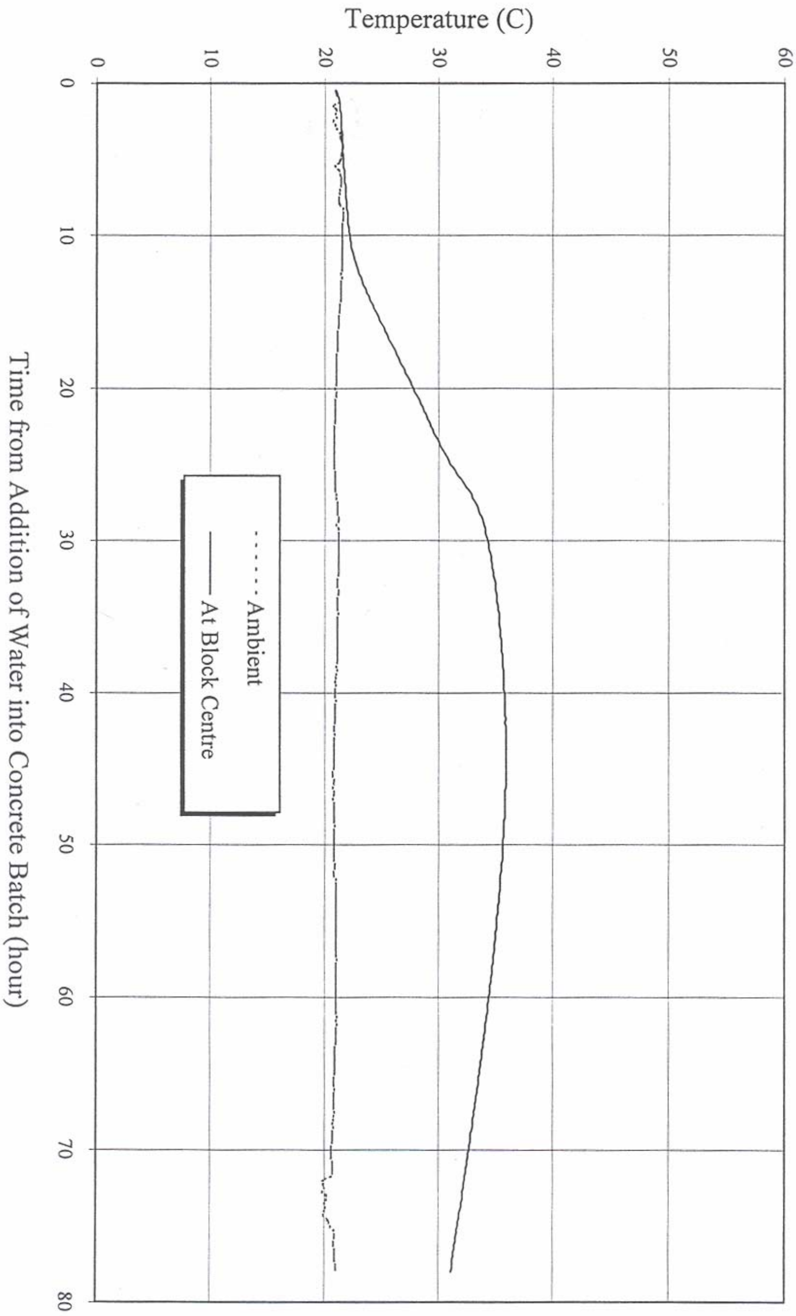


Table 3.4-1 Test Results of Temperature Development in Concrete

Mix No.	**M-22**	**M-28**	**M-23**	**M-30**	**M-24**	**M-26**	**M-27**
Binder Content (kg/m^3)	400		450		500		
Water/Binder Ratio	0.40		0.35		0.35		
Binder Type	PC	8% SF+ 30% FA	PC	8% SF+ 30% FA	PC	20%FA+ 35%SG	20%FA+ 50%SG
Initial Ambient Temp. (°C)	24.0	11.6	16.2	11.4	14.0	20.9	20.9
Initial Concrete Temp. (°C)	25.0	12.0	18.0	12.5	15.2	20.9	21.0
Max. Concrete Temp. (°C)	56.3	30.5	52.1	33.2	50.7	45.3	35.9
Max. Temp. Rise (°C)	**32.3**	**18.9**	**35.9**	**21.8**	**36.7**	**24.4**	**15.0**
Ratio to PC Mix	1	0.585	1	0.607	1	0.665	0.409
Time to Max. Temp. (h)	**20.5**	**32.0**	**23.0**	**28.5**	**27.0**	**32.5**	**42.3**
Ratio to PC Mix	1	1.56	1	1.24	1	1.20	1.57

The other PC mix M-22 had the lowest cement content of 400 kg/m^3 but a higher w/c ratio of 0.40 compared to 0.35 of M-23 and M-24. Within the three PC mixes, M-22 recorded the lowest maximum temperature rise of 32.3 °C as well as the shortest time of 20.5 hours to reach the maximum temperature.

These observations were in consistence with the general knowledge that higher cement contents increase the total heat of cement hydration; thus result in higher temperatures in concrete.

Ternary Concrete Type I: PC +8%SF +30%FA

It has been observed in the BRC binary concrete investigation that, the maximum temperature rise was almost unaffected in the 8% silica fume mix but reduced significantly in either the fly ash mixes or slag mixes, when compared to that of the PC control mix.

In this investigation, the ternary mixes with 8%SF and 30%FA (M-28 and M-30) recorded the maximum temperature rises of 18.9 °C and 21.8 °C. Comparing to their PC control mixes M-22 and M-23, these two ternary mixes had the respective reduction of 41% and 39% in the maximum temperature rise.

The time lapses taken to achieve the maximum temperature in the two ternary mixes were much longer than (1.56 or 1.24 times) that in the PC controls. It can also be observed in Fig 3.4-1 to Fig 3.4-4 that the rates of temperature drop after the peak were also much lower in the ternary mixes than that in the PC mixes.

The results of the ternary mix M-28 (8%SF +30%FA) was also compared to that of three binary mixes, M-7, M-12 and M-14 based on the same binder content (400 kg/m^3) and w/b ratio (0.40). While the maximum temperature rise in M-7 with 8%SF was 32.2 °C, that of M12 and M-14 containing 20% and 40%FA were 21.9 °C and 17.6 °C. Regardless of the additional 8%SF in the ternary mix, M-28 then had the temperature rise (18.9 °C) between that of the binary mixes with 20% and 40% FA respectively. These results indicated that, in the ternary mixes containing both SF and FA, only the fly ash plays the significant role in reducing temperature rise in the concrete.

In summary, the ternary concrete mixes (M-28 and M-30) with 8%SF and 30%FA in the binder reduced the maximum temperature rise by 41% and 39% compared to their PC control mixes. The fly ash was found to be the key ingredient in reducing temperature rise in these ternary mixes, while the silica fume had insignificant effect on the temperature rise. The temperature rise before the peak and the drop after the peak were both in much lower rates in the ternary mixes than that in the PC mixes. The lower maximum temperatures and the lower rates of temperature change reduce the thermal gradient and thermal stresses; thus reducing the potential of thermal cracking in the ternary concrete.

Ternary Concrete Type II: PC +20%FA +(35 or 50)%Slag

It has been found in the BRC binary concrete project that, the mixes containing 20%FA, 35%Slag or 50%Slag in the binary binder (400 kg/m^3 and w/b of 0.40) all had significantly lower temperature rise than the PC control concrete. The maximum temperature rises in these three binary mixes were 21.9 °C, 26.7 °C and 16.8 °C comparing to that of 32.3 °C in the PC mix.

In this investigation of ternary concrete mixes, two ternary mixes containing 20%FA plus 35%Slag (M-26) or 50%Slag (M-27) both recorded much lower temperature rises than the PC control mix (M-24) of the same binder content of 500 kg/m^3 and w/b ratio of 0.35. While the PC mix had the maximum temperature rise of 36.7 °C, the ternary mixes M-26 and M-27 recorded that of 24.4 °C and 15.0 °C; in other wards, a reduction by 34% and 59% respectively.

The time lapses taken to reach the peak temperature in the two ternary mixes were also much longer (1.20 and 1.57 times) than that in the PC control. As shown in Fig .3.4-5 to Fig 3.4-7, the rate of temperature drop after the peak was significantly lower in the ternary mixes than that in the PC mix.

In summary, the ternary concrete mixes containing both FA and SG in the binder reduced the maximum temperature rise by 34% and 59% compared to the PC control mix. The increase of slag content from 35% to 50% in the ternary binders resulted in further reduction in the maximum temperature rise. The rates of temperature rise before the peak and the drop after the peak were both much lower than that in the PC mixes. The lower maximum temperatures and the lower rates of temperature change in the ternary mixes reduce the potential of thermal cracking in concrete.

3.5 COMPRESSIVE STRENGTH

The compressive strength of each of the nine concrete mixes was tested at 3, 28 and 91 days according to AS 1012, Part 9. All the cylinders were cured in lime saturated water at 23°C until the age of testing. Two 100-mm diameter cylinders were tested at each age.

Table 3.5-1 and Fig 3.5-1 present all the test results on compressive strength. Overall, the compressive strength of the nine concrete mixes at 28 days was in the range of 49.6 to 68.9 MPa. The compressive strength also ranged from 19.5 to 47.8 MPa at 3 days and 58 to 83.4 MPa at 91 days.

Table 3.5-1 Test Results of Compressive Strength

<table>
<tr><th rowspan="2">Mix No.</th><th rowspan="2">Binder Type</th><th rowspan="2">Binder (kg/m3)</th><th rowspan="2">w/b Ratio</th><th colspan="2">3 Day Test</th><th colspan="2">28 Day Test</th><th colspan="2">91 Day Test</th></tr>
<tr><th>f’c (MPa)</th><th>Ratio to PC mix</th><th>f’c (MPa)</th><th>Ratio to PC mix</th><th>f’c (MPa)</th><th>Ratio to PC mix</th></tr>
<tr><td>M22</td><td>PC</td><td rowspan="2">400</td><td rowspan="2">0.40</td><td>36.0</td><td>1</td><td>53.8</td><td>1</td><td>58.0</td><td>1</td></tr>
<tr><td>M 28</td><td>8%SF+ 30%FA</td><td>22.6</td><td>0.628</td><td>49.6</td><td>0.922</td><td>61.7</td><td>1.064</td></tr>
<tr><td>M 23</td><td>PC</td><td rowspan="4">450</td><td rowspan="4">0.35</td><td>45.9</td><td>1</td><td>68.9</td><td>1</td><td>76.0</td><td>1</td></tr>
<tr><td>M25</td><td>20%FA+ 50%SG</td><td>19.5</td><td>0.425</td><td>50.2</td><td>0.729</td><td>60.8</td><td>0.800</td></tr>
<tr><td>M29</td><td>8%SF+ 20%FA</td><td>34.7</td><td>0.756</td><td>65.0</td><td>0.943</td><td>70.9</td><td>0.933</td></tr>
<tr><td>M30</td><td>8%SF+ 30%FA</td><td>30.7</td><td>0.669</td><td>64.5</td><td>0.936</td><td>71.6</td><td>0.942</td></tr>
<tr><td>M 24</td><td>PC</td><td rowspan="3">500</td><td rowspan="3">0.35</td><td>47.8</td><td>1</td><td>66.9</td><td>1</td><td>72.8</td><td>1</td></tr>
<tr><td>M 26</td><td>20%FA+ 35%SG</td><td>28.0</td><td>0.586</td><td>66.4</td><td>0.993</td><td>83.4</td><td>1.146</td></tr>
<tr><td>M 27</td><td>20%FA+ 50%SG</td><td>21.8</td><td>0.456</td><td>55.0</td><td>0.822</td><td>68.1</td><td>0.935</td></tr>
</table>

PC Concrete

The PC concrete mixes M-23 and M-24 had the same w/c ratio of 0.35 but different cement content of 450 and 500 kg/m^3. At the age of 28 and 91 days, the compressive strengths of the richer mix M-24 were 66.9 and 72.8 MPa, which were slightly lower than the corresponding values of 68.9 and 76.0 MPa of the leaner mix M-23. These observations are in consistence with the findings of other investigators that a leaner concrete mix leads to a higher strength under the same w/c ratio. However, at the age of 3 days, a higher compressive strength of 47.8 MPa was achieved in the richer mix M-24 compared to 45.9 MPa in M-23. The higher early strength of a richer mix was not unexpected and could be due to the higher temperature in the concrete, which accelerated the strength gain at earlier ages. Nevertheless, the cement content is only a secondary factor in the strength of concrete and the difference in concrete strengths due to cement contents is not significant, as shown in the above test results.

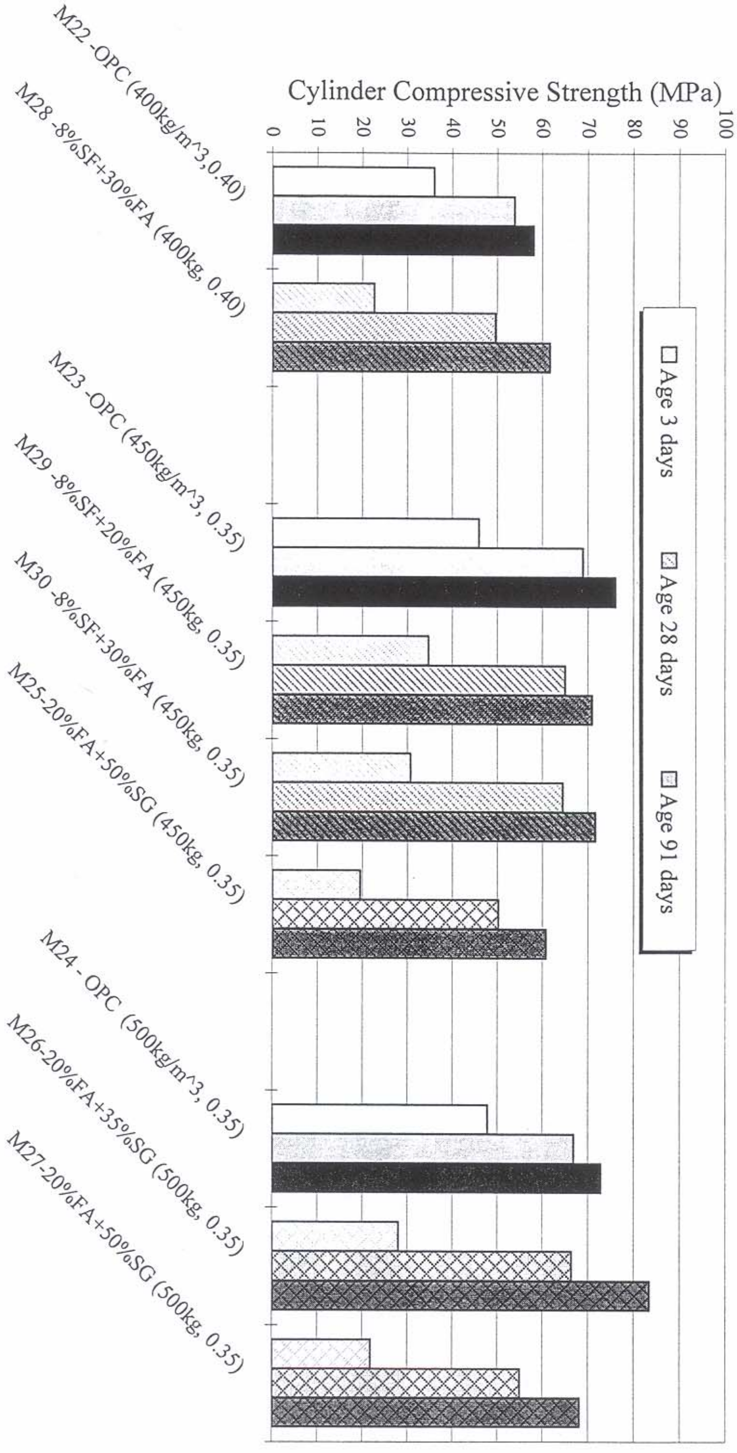


Fig 3.5-1 Compressive Strength at Age of 3, 28 and 91 Days

The other PC mix M-22 had the lowest cement content of 400 kg/m^3 but a higher w/c ratio of 0.40 compared to 0.35 of M-23 and M-24. M-22 also recorded much lower compressive strengths at all the three ages (3, 28 and 91 days) than that of M-23 and M-24. These results verified that the w/c ratio has a much more significant effect on the strength of concrete than the cement content.

Ternary Concrete Type I: PC +8%SF +(20 or 30)%FA

It has been found in the BRC binary concrete investigation that, the binary mixes with equal-mass replacement of PC with 4%, 8% or 12% silica fume had higher compressive strength than the PC mixes at all the ages of 3, 28 and 91 days. The binary mixes containing 20%, 30% or 40% fly ash generally had lower strength than the PC mixes but some FA mixes developed higher strengths than the PC mixes at 91 days.

In this investigation, three mixes of this ternary binder generally had lower compressive strength than the PC mixes at 3, 28 and 91 days, except for M-28 which developed a slightly higher strength than the PC mix M-22 at 91 days. The strength ratios of the three ternary mixes to the PC mixes were in the range of 0.63 to 0.76 at 3-days, 0.92 to 0.94 at 28-days and 0.93 to 1.06 at 91 days.

The mixes M-29 and M-30 were different only in that M-29 contained 20% fly ash while M-30 contained 30% fly ash in the ternary binder. As could be expected, M-29 had less percentage of fly ash in its binder and achieved a higher strength than M-30 at the early age of 3 days. In the later ages of 28 and 91 days, however, the differences in strength gain in the two ternary mixes were negligible.

The results of the ternary mix M-28 (8%SF +30%FA) was directly comparable to that of two binary mixes, M-7 and M-13, based on the same binder content (400 kg/m^3) and w/b ratio (0.40). M-7 contained 8%SF while M-13 had 30% FA in the binary binder. Table 3.5-2 presents the compressive strengths of these three binary and ternary mixes and the PC control mix for comparison.

Table 3.5-2 Comparison of Results of Binary and Ternary Mixes

Mix No.	Binder Type	Binder (kg/m3)	w/b Ratio	3 Day Test		28 Day Test		91 Day Test	
				f'c (MPa)	Ratio to PC mix	f'c (MPa)	Ratio to PC mix	f'c (MPa)	Ratio to PC mix
M22	**PC**	400	0.40	**36.0**	**1**	**53.8**	**1**	**58.0**	**1**
M-7	8% SF			37.3	1.04	65.8	1.22	72.2	1.25
M-13	30% FA			23.8	0.66	50.0	0.93	63.1	1.09
M 28	8%SF+ 30%FA			22.6	0.63	49.6	0.92	61.7	1.06

It is shown in Table 3.5-2 that the ternary mix M-28 (8%SF+30%FA) had slightly lower strengths as the binary mix M-13 (30%FA) at all the ages. In this case, the additional replacement of PC with 8% silica fume did not enhance concrete strengths as one would have expected.

Other results comparable between the binary and ternary concretes are very few in the literature. However, the research work on ternary (PC+SF+FA) concretes by Ozyildirim et al (Ozyildirim et al, 1994, ACI Materials Journal) was found to contain some comparable results with the above finding in the BRC investigation. Two types of Portland cements, Type II (modified cement) and Type III (rapid hardening cement), and the Class-F fly ash were used in their concrete mixes and the w/b ratio was 0.44. Table 3.5-3 presents part of the relevant test results (tested at 23 °C) from their experimental investigation.

Table 3.5-3 Test Results on Ternary Mixes by Ozyildirim et al (1994)

Mix No.	Binder Type	Binder (kg/m3)	w/b Ratio	1 Day Test		7 Day Test		28 Day Test	
				f'c (MPa)	Ratio to PC mix	f'c (MPa)	Ratio to PC mix	f'c (MPa)	Ratio to PC mix
M-1	**Type II**	**377**	0.44	**18.68**	**1**	**29.58**	**1**	**36.40**	**1**
M-2	3%SF+ 32%FA	357		10.07	0.539	20.48	0.692	35.03	0.962
M-5	10%SF+ 35%FA	351		9.51	0.509	19.03	0.643	36.34	0.998
M-1A	**Type III**	**377**	0.44	**26.06**	**1**	**34.34**	**1**	**41.71**	**1**
M-2A	3%SF+ 32%FA	357		15.93	0.611	26.75	0.779	40.33	0.967
M-5A	10%SF+ 35%FA	351		9.93	0.381	21.93	0.639	32.34	0.775

It is found in Table 3.5-3 that the ternary mixes with a higher silica fume content (10%SF+35%FA) had lower compressive strengths than that with a lower silica fume content (3%SF+32%FA) at 1, 7 and 28 days for both Type II and Type III cements.

The available test results from this BRC investigation and in the above literature appeared to indicate that the further replacement of PC with silica fume in fly ash concrete was of little benefits on the strength gain (in both early and later ages) of the concrete.

In summary, the ternary concrete mixes with 8%SF and 20 or 30%FA in the binder generally had lower compressive strengths than the PC mixes at 3, 28 and 91 days. The test results from this investigation and from a research work in the literature indicated that the addition of silica fume into the binder with certain amounts of fly ash was of little benefits on the strength gain (in both early and later ages) of the concrete. However, further investigations are necessary before such a conclusion can be drawn and to find out the mechanisms of the appeared "mismatch" between silica fume and fly ash on strength gain.

Ternary Concrete Type II: PC +20%FA +(35 or 50)%Slag

In the BRC binary concrete investigation, the compressive strengths of the 20%FA concrete were lower than the PC mix at 3 and 28 days, but higher at 91 days. For the mixes with 35% or 50% slag in the binary binder, the compressive strengths were higher than the PC mixes except at 3 days.

Three mixes containing 20%FA and 35% or 50% slag in the ternary binder were investigated in this project. However, the test results were not directly comparable to that of the binary mixes with fly ash or slag, since the binder content and w/b ratio of the three ternary mixes were not the same as that of the binary mixes.

In general, three ternary mixes with both fly ash or slag had lower compressive strength than the PC mixes at 3, 28 and 91 days, except for M-26 which developed a higher strength than the PC mix at 91 days. The strength ratios of the three ternary mixes to the PC mixes were in the range of 0.43 to 0.59 at 3-days, 0.73 to 0.99 at 28-days and 0.80 to 1.15 at 91-days.

M-25 (20%FA +50%Slag) was also found to have lower strengths than the ternary mixes (M-29 and M-30) containing SF +FA within the group with binder content of 450 kg/m^3 and w/b of 0.35 (see Table 3.5-1).

For the two comparable mixes with different slag contents, the mix with higher slag content, M-27 (20%FA +50%Slag), had lower strengths than M-26 (20%FA +35%Slag) at all ages. For concrete with a binary binder of PC and slag, the binder with 50% slag was found to have the optimal strength gain within the binders with slag contents of 35, 50 and 65 percent. However, for the ternary binder containing both of fly ash and slag, a slag content lower than 50 percent was found to be beneficial to the strength gain.

Comparing the results of M-25 and M-27 on the effect of binder content on strength, the richer mix M27 had higher strengths than the leaner mix M-25 at all the ages. This observation was opposite to that of the effect of binder content on strength of the PC mixes M-23 and M-24 at 28 and 91 days.

In general, the ternary mixes with 20%FA and 35 to 50%SG in the binder had lower strengths than the PC mixes at 3, 28 and 91 days, except for M-26 which had 35% slag content and developed a higher strength than the PC mix at 91 days. The richer ternary mix of this type was found to have higher strengths at all ages, which was opposite to the effect of cement content on strength of PC concrete. The early age strengths of these ternary mixes were much lower than PC mixes and care must then be taken in applications to determine the appropriate time to remove moulds. However, ternary mixes of this type can be very attractive to such applications involving a continuous pour of large quantities of concrete due to the longer setting times and much lower heat generation in these mixes as shown in the test results of this investigation.

3.6 CHLORIDE PENETRATION

Four different chloride penetration test methods were used in this investigation: the "rapid chloride permeability test (ASTM C1202 or AASHTO-T277)", "3% NaCl static ponding test", "15% NaCl static ponding test" and "15% NaCl cyclic ponding test". The later three test methods are developed or modified by the BRC. The results of these tests are used to analyse the significance of these methods as well as to compare the correlation among the test results.

Except for the 3% NaCl static ponding test, the effect of the specimen age was also investigated with the other three methods by conducting the tests at the age of 28 and 182 days respectively.

3.6.1 ASTM C1202 TEST AT 28 AND 182 DAYS

The test procedures were according to the ASTM C1202-91, which was derived from and equivalent to the AASHTO-T277 method. The following Table 3.6-1 presents the criteria given in ASTM C1202 on the judgement of chloride ion penetrability in concrete based on the total electrical charge passed during a six-hour test and indicated by coulomb values.

Table 3.6.1-1. Chloride Ion Penetrability Based on Charge Passed

Charge Passed (coulombs)	Chloride Ion Penetrability
>4,000	High
2,000-4,000	Moderate
1,000-2,000	Low
100-1,000	Very Low
<100	Negligible

All the nine concrete mixes in this project were tested at the specimen age of 28 days and 182 days to compare the effect of aging of concrete on the test results. All specimens were cured in lime saturated water at 23 °C until testing. The tests were carried out in a temperature-controlled room at 23 °C.

Table 3.6.1-2 and Fig 3.6.1-1 present the ASTM C1202 test results of all the concrete mixes at 28 days and at 182 days. The nine mixes were divided into three groups according to binder content and w/b ratio. The binder contents range from 400 to 500 kg/m3 and the w/b ratios from 0.35 to 0.40. In each of the three groups, the concrete mixes had the same binder content and w/b ratio; a PC control mix was also included.

Table 3.6.1-2. ASTM C1202 Test Results at 28 and 182 Days

Mix No.	Binder Type	Binder (kg/m3)	w/b Ratio	28 Day Test		182 Day Test		Ratio of 182/28D Results
				Charge (Coulomb)	Ratio to PC mix	Charge (Coulomb)	Ratio to PC mix	
M22	**PC**	400	0.40	**3668**	**1**	**2392**	**1**	**0.65**
M 28	8%SF+ 30%FA			1630	0.44	345	0.14	0.21
M 23	**PC**	450	0.35	**3047**	**1**	**2437**	**1**	**0.80**
M25	20%FA+ 50%SG			1216	0.40	371	0.15	0.31
M29	8%SF+ 20%FA			1289	0.42	320	0.13	0.25
M30	8%SF+ 30%FA			1127	0.37	236	0.10	0.21
M 24	**PC**	500	0.35	**3780**	**1**	**2331**	**1**	**0.62**
M 26	20%FA+ 35%SG			1794	0.47	365	0.16	0.20
M 27	20%FA+ 50%SG			1197	0.32	396	0.17	0.33

Overall, the test results of all the concrete mixes were in the range of 1127 to 3780 coulombs at the specimen age of 28 days and in the range of 236 to 2437 coulombs at 182 days. According to the criteria given in Table 3.6.1-1, the chloride ion penetrability in the six ternary mixes was "very low" and that in the three PC mixes was at the level of "moderate".

PC Concrete

At 28 Days

The PC concrete mixes M-23 and M-24 had the same w/c ratio but different cement content of 450 and 500 kg/m^3. At the age of 28 days, the electrical charge of the richer mix M-24 were 3780 coulombs, which was significantly higher than the value of 3047 coulombs of the leaner mix M-23. The significant increase in coulomb values with higher cement contents was also observed in the BRC binary concrete investigation within three PC mixes with w/c ratio of 0.40 and cement content of 350, 400 and 450 kg/m^3.

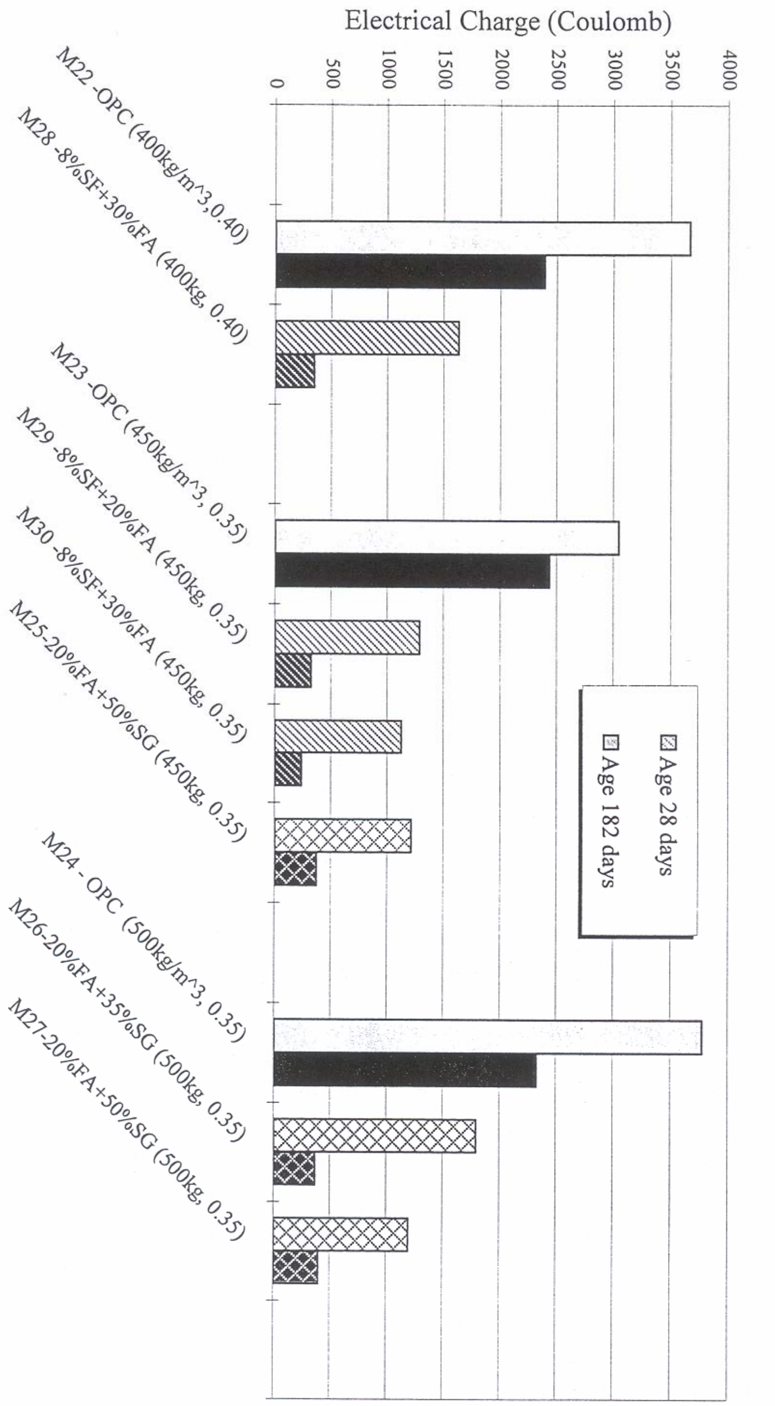


Fig 3.6.1-1 ASTM C1202 Test Results at Age of 28 and 182 Days

In the BRC report on binary concrete investigation (Chang et al. 1998), it was pointed out that the increase in coulomb value with an increase in binder content might be due to the higher calcium hydroxide content in a richer mix. Other investigators (Feldman et al. 1994; Cao et al. 1996) also found that higher hydroxyl ions (OH^-) in the pore solution can result in higher coulomb values in the ASTM C1202 tests. The significant variation in coulomb values due to hydroxyl ions rather than chloride ions could mislead the evaluation of chloride penetrability in concrete based on the ASTM C1202 test. Further research work is needed on the assessment of suitability of the ASTM C1202 method itself.

The other PC mix M-22 had the lowest cement content of 400 kg/m^3 but a higher w/c ratio of 0.40 compared to 0.35 of M-23 and M-24. M-22 recorded the coulomb value higher than M-23 but slightly lower than M-24.

At 182 Days

All three PC mix recorded lower charges at 182 days in the tests. The ratio of the coulomb value at 182 days to that at 28 days was 0.65, 0.80 and 0.62 for M-22, M-23 and M-24 respectively. It was interesting to note that the ranking of the test results of the three PC mixes became opposite to that at 28 days due to the quite different reduction in the charge of the three mixes at 182 days. However, the differences between the coulomb values of the three PC mixes were not significant at 182 days.

Ternary Concrete Type I: PC +8%SF +(20 or 30)%FA

At 28 Days

It has been found in the BRC binary concrete investigation that, the ratio of coulomb values of a binary mix to the PC mix was 0.36 for the 8% silica fume mix and was 0.82 and 0.80 for the 20% and 30% fly ash mixes.

In this investigation, three mixes of this ternary binder all had much lower electrical charges than the PC mixes at 28 days. The ratio of the test results of the three ternary mixes to the PC mix was 0.44, 0.42 and 0.37 for M-28, M-29 and M-30 respectively.

The mixes M-29 and M-30 contained 20% fly ash and 30% fly ash in the ternary binder with 8% silica fume. Similar to that in the binary mixes, M-30 with a higher fly ash content in the ternary binder recorded a slightly lower charge than M-29.

The results of the ternary mix M-28 (8%SF +30%FA) was compared to that of two binary mixes, M-7 and M-13, based on the same binder content (400 kg/m^3) and w/b ratio (0.40). Table 3.6.1-3 presents the test results of these three mixes and the PC control mix at both 28 and 182 days.

M-7 contained 8%SF while M-13 had 30% FA in the binary binder. While M-7 and M-13 recorded the charge of 1308 and 2931 coulombs respectively, M-28 had the result of 1630 coulombs. The replacement of further 8% of PC with silica fume in a 30% fly ash mix resulted in the charge to drop significantly and to be close to that of the binary mix with 8% silica fume.

Table 3.6.1-3. Comparison of 28-Day Results of Binary and Ternary Mixes

Mix No.	Binder Type	Binder (kg/m3)	w/b Ratio	28 Day Test		182 Day Test		Ratio of 182/28D Results
				Charge (Coulomb)	Ratio to PC mix	Charge (Coulomb)	Ratio to PC mix	
M22	**PC**	400	0.40	**3668**	**1**	**2392**	**1**	**0.65**
M-7	8%SF			1308	0.36	710	0.30	0.54
M-13	30%FA			2931	0.80	293	0.12	0.10
M 28	8%SF+ 30%FA			1630	0.44	345	0.14	0.21

<u>At 182 Days</u>

All the three mixes of this ternary binder tested at 182 days had significant reduction in the electrical charge compared to that at 28 days. The ratio of the coulomb value at 182 days to that at 28 days was in the range of 0.21 to 0.25 for the three mixes. These ratios were also much lower than that of 0.65 and 0.80 of the PC mixes. The reduction in electrical charge was more pronounced in these ternary mixes than that in the PC mix with the increased age of specimens. It is shown in Table 3.6.1-2 that the ratios of coulomb values of the three ternary mixes to that of the PC mix dropped from the range of 0.37 to 0.44 at 28 days to that of 0.10 to 0.14 at 182 days.

Comparing the results of M-29 and M-30 at 182 days, the same as that in the tests at 28 days, M-30 with a higher fly ash content still had a slightly lower charge than M-29.

The above Table 3.6.1-3 includes the comparison of the test results of M-28 (8%SF +30%FA) to that of the two binary mixes, M-7 (8%SF) and M-13 (30%FA), at 182 days. It was found in the BRC binary concrete investigation that the effect of aging in water on reduction in coulomb value was much more significant in fly ash concrete than in silica fume concrete. The coulomb values were reduced by 90% in the fly ash mix M-13, 46% in the silica fume mix M-7 and 35% in the PC mix M-22. Because of the dramatic reduction in the charge in fly ash concrete, the performance of the fly ash concrete ranked the best at 182 days, while that was below the silica fume concrete and slag concrete at 28 days.

In Table 3.6.1-3, the reduction in coulomb value of M-28 (8%SF +30%FA) at 182 days was 79% in comparison to that at 28 days, which was much higher than that in M-7 (8%SF) but slightly lower than in M-13 (30%FA). The age effect in this type of ternary concrete was between those in the binary concretes containing 8% silica fume and 30% fly ash.

Ternary Concrete Type II: PC +20%FA +(35 or 50)%Slag

<u>*At 28 Days*</u>

In the BRC binary concrete investigation, the ratio of coulomb values of a binary mix to the PC mix was 0.82 for the 20% fly ash mix and was 0.45 and 0.36 for the 35% and 50% slag mixes.

Three mixes containing 20%FA and 35% or 50% slag in the ternary binder were investigated in this project. However, the test results were not directly comparable to that of the binary mixes with fly ash or slag, since the binder content and w/b ratio of the three ternary mixes were not the same as that of the binary mixes.

In this investigation, the three ternary mixes all had much lower electrical charges than the PC mixes at 28 days. The ratio of the test results of the three ternary mixes to the PC mix was 0.40, 0.47 and 0.32 for M-25, M-26 and M-27 respectively.

M-25 (20%FA +50%Slag) was also found to have the result between those of the other two ternary mixes (M-29 and M-30) containing SF +FA within the group with binder content of 450 kg/m^3 and w/b of 0.35 (see Table 3.6.1-2).

For the two mixes with different slag contents, the mix with higher slag content, M-27 (20%FA +50%Slag), recorded lower coulomb value than M-26 (20%FA +35%Slag) at 28 days. This result was similar to that in the binary concrete tests, in which the increase in the replacement ratio of slag in the binary binder resulted in decrease in the measured coulomb values.

Comparing the results of M-25 and M-27 on the effect of binder content, the richer mix M27 had a slightly lower charge than the leaner mix M-25. This observation was opposite to that of the effect of binder content on the ASTM C1202 test results of the PC mixes M-23 and M-24 at 28 days. It was found in the binary concrete investigation, however, the effect of binder content on binary fly ash concrete was opposite to that on PC and binary concrete containing silica fume or slag.

Table 3.6.1-4. Comparison of 28-Day Results of Binary and Ternary Mixes

Mix No.	Binder Type	Binder (kg/m3)	w/b Ratio	Charge (Coulomb)	Relative Ratio	Trend with Increased Binder
M13	30%FA	**400**	**0.40**	2931	1	Decrease
M16	30%FA	**450**		2394	0.82	
M-18	50%Slag	**400**	**0.40**	1304	1	Increase
M20	50%Slag	**450**		1668	1.28	
M 25	20%FA+ 50%SG	**450**	**0.35**	1216	1	Nearly Unchanged
M 27	20%FA+ 50%SG	**500**		1197	0.98	

Table 3.6.1-4 presents the test results of the binary fly ash mixes and slag mixes and compares these results to that of the ternary mixes. The opposite trend in the measured coulomb values was shown in the table within the binary fly ash or slag mixes. Therefore, the little effect of binder content on the test results of M-25 and M-27 appeared to be due to offset of the opposite effects of fly ash and slag in the ternary binder.

At 182 Days

Compared to that at 28 days, all the three mixes containing both fly ash and slag at 182 days had significant reduction in the electrical charge (see Table 3.6.1-2). The ratio of the coulomb value at 182 days to that at 28 days was in the range of 0.20 to 0.33 for the three mixes. These ratios were much lower than that of 0.62 and 0.80 of the PC mixes. The reduction in electrical charge with the age of specimens was then more pronounced in these ternary mixes than that in the PC mix. As shown in Table 3.6.1-2 that the ratios of coulomb values of the three ternary mixes to that of the PC mix reduced from the range of 0.32 to 0.47 at 28 days to that of 0.15 to 0.17 at 182 days.

Opposite to the 28-day results of the two ternary mixes with 35% and 50% slag in the binder, the mix with higher slag content (M-27) recorded a slightly higher coulomb value than M-26 at 182 days. However, the difference between the two values was not significant.

Comparing the results of M-25 and M-27 at 182 days, the effect of binder content was also as little as that at 28 days, although the coulomb value of the richer mix M27 became slightly higher than the leaner mix M-25 at 182 days.

3.6.2 STATIC PONDING IN 3% NaCl SOLUTION OVER 91 DAYS

The 3% NaCl concentration in the solution and the 91-days ponding duration of this test is similar to that of the AASHTO T259 test. However, instead of the analysis of chloride content at different depths in a specimen, the depth of water soluble chloride penetration is determined by the spraying of $AgNO_3$ solution onto the broken specimen section. This procedure greatly reduces the cost of a test and makes it a very simple test.

All the nine concrete mixes were tested for chloride penetration in this test with 10011001200 mm prism specimens. The specimens were moist cured in moulds for one day, followed by lime-water curing to 7 days, then air-cured at 23 °C until commencement of immersion test at 28 days.

Table 3.6.2-1 and Fig 3.6.2-1 show the chloride penetration depth of all the nine concrete mixes divided into three groups according to binder content and w/b ratio.

Fig 3.6.2-1 Chloride Penetration in Static Ponding Test: SP(3%) - 91d

(in 3% NaCl solution over 91 days from age 28 days)

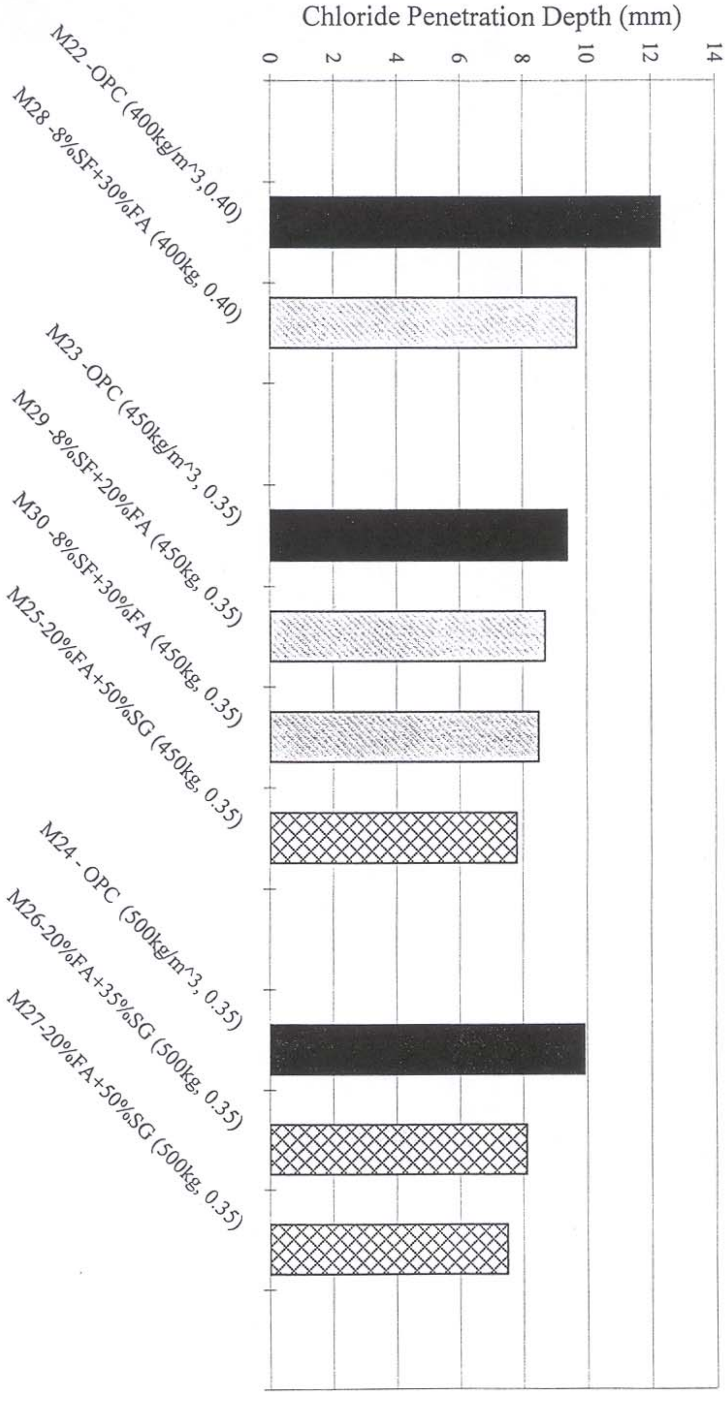


Table 3.6.2-1. Test Results of Static Ponding in 3% NaCl Solution over 91 Days

Mix No.	Binder Type	Binder Content (kg/m^3)	W/b Ratio	Static Ponding (3% NaCl) over 91 Days	
				Chloride Penetration Depth (mm)	Ratio to PC Mix
M 22	**PC**	400	0.40	**12.3**	**1**
M 28	8%SF+30%FA			9.7	0.79
M 23	**PC**	450	0.35	**9.4**	**1**
M 25	20%FA+50%SG			7.8	0.83
M 29	8%SF+20%FA			8.7	0.93
M 30	8%SF+30%FA			8.5	0.90
M 24	**PC**	500	0.35	**9.9**	**1**
M 26	20%FA+35%SG			8.1	0.82
M 27	20%FA+50%SG			7.5	0.76

Overall, the chloride penetration depths in the nine concrete mixes over 91-days ponding were in the range of 7.5 to 12.3 mm. All the ternary concrete mixes had less chloride penetration than the PC control mixes. However, as shown in Fig 3.6.2-1 to that in Fig 3.6.1-1, the differences in the chloride penetration between the ternary and PC concretes were much less pronounced than that in coulomb values of the ASTM C1202 test.

PC Concrete

The PC concrete mixes M-23 and M-24 were different in their cement contents of 450 and 500 kg/m^3 respectively. The difference between their 91-days chloride penetration results was insignificant. This observation is consistent to that in the BRC binary concrete investigation, in which little variation in chloride penetration were measured in three PC mixes with w/c ratio of 0.40 and cement content of 350, 400 and 450 kg/m^3.

The other PC mix M-22 had the lowest cement content of 400 kg/m^3 but a higher w/c ratio of 0.40 compared to 0.35 of M-23 and M-24. M-22 recorded a significantly higher chloride penetration than M-23 and M-24. This indicated that w/c ratio had much more pronounced effect on the 91-days ponding results than cement content.

Ternary Concrete Type I: PC +8%SF +(20 or 30)%FA

It was found in the BRC binary concrete investigation that, the ratio of chloride penetrations of a binary mix to the PC mix was 0.43 for the 8% silica fume mix and was 0.76 and 0.67 for the 20% and 30% fly ash mixes.

In this investigation, three mixes of this ternary binder all had lower chloride penetration than the PC mixes after 91-days ponding in 3% NaCl solution. The ratio of the test results of the three ternary mixes to the PC mix was 0.79, 0.93 and 0.90 for M-28, M-29 and M-30 respectively. The ratios are, however, much higher than that of ASTM C1202 results of 0.44, 0.42 and 0.37 for the same three ternary mixes.

The mixes M-29 and M-30 contained 20% fly ash and 30% fly ash in the ternary binder with 8% silica fume. Similar to that in the binary mixes, M-30 with a higher fly ash content in the ternary binder had nearly the same but a slightly lower chloride penetration than M-29.

The results of the ternary mix M-28 (8%SF +30%FA) was compared to that of two binary mixes, M-7 and M-13, based on the same binder content (400 kg/m^3) and w/b ratio (0.40). M-7 contained 8%SF while M-13 had 30% FA in the binary binder. Table 3.6.2-2 presents the test results of these three mixes and the PC control mix.

Table 3.6.2-2. Comparison of Results of Binary and Ternary Mixes

Mix No.	Binder Type	Binder Content (kg/m^3)	W/b Ratio	Static Ponding (3% NaCl) over 91 Days	
				Chloride Penetration Depth (mm)	Ratio to PC Mix
M22	**PC**	400	0.40	**12.3**	**1**
M-7	8%SF			5.3	0.43
M-13	30%FA			8.2	0.67
M 28	8%SF+ 30%FA			9.7	0.79

While M-7 and M-13 recorded the chloride penetration depth of 5.3 and 8.2 mm respectively, M-28 had a higher chloride penetration of 9.7 mm. The ternary mix M-28 in this case had higher chloride penetration than both of the binary mixes.

Ternary Concrete Type II: PC +20%FA +(35 or 50)%Slag

In the BRC binary concrete investigation, the ratio of chloride penetration of a binary mix to that of the PC mix was 0.76 for the 20% fly ash mix and was 0.61 and 0.41 for the 35% and 50% slag mixes. The concrete mixes in the tests had the binder content of 400 kg/m^3 and w/b ratio of 0.40.

Three mixes containing 20%FA and 35% or 50% slag in the ternary binder were investigated in this project. However, the test results were not directly comparable to that of the binary mixes with fly ash or slag, since the binder content and w/b ratio of the three ternary mixes were not the same as that of the binary mixes.

In this investigation, the three ternary mixes all had lower chloride penetrations than the PC mixes. The ratio of the test results of the three ternary mixes to the PC mix was not, however, as low as that in the ASTM C1202 tests. These ratios in the 91-days ponding tests were 0.83, 0.82 and 0.76 for M-25, M-26 and M-27, compared to that in the ASTM C1202 tests of 0.40, 0.47 and 0.32.

Within the group with the binder content of 450 kg/m^3 and w/b of 0.35 (see Table 3.6.2-1), M-25 (20%FA +50%Slag) had a lower chloride penetration than the other two ternary mixes (M-29 and M-30) containing SF +FA.

For the two mixes with different slag contents, the mix with higher slag content, M-27 (20%FA +50%Slag), recorded a lower chloride penetration than M-26 (20%FA +35%Slag). This result was similar to that in the binary concrete tests, in which the increase of slag content from 35% to 50% in the binary binder resulted in decrease in the chloride penetration.

Comparing the results of M-25 and M-27 on the effect of binder content, the richer mix M27 had nearly the same but a slightly lower chloride penetration than the leaner mix M-25.

3.6.3 STATIC PONDING IN 15% NaCl SOLUTION OVER 14 DAYS

The 15% NaCl solution static ponding test was developed at the BRC in order to accelerate chloride penetration and to reduce the duration of the test, by using a higher concentration of NaCl in the solution. This test was conducted with all the nine mixes over a period of 14 days but at the age of 28 and 182 days to compare the effects of specimen age on the test results.

The size and curing regime of the specimens were the same as that in the 91-days static ponding test. The specimens were moist cured in moulds for one day, followed by lime-water curing to 7 days, then air-cured at 23 °C until commencement of immersion test at 28 days or 182 days. The water-soluble chloride penetration depth in a specimen was also determined in the same way as that in the 91-days ponding test.

Table 3.6.3-1 and Fig 3.6.3-1 present the results of chloride penetration of all the nine concrete mixes tested at 28 days and at 182 days. The nine mixes were divided into three groups according to binder content and w/b ratio.

Overall, the chloride penetration depths in the nine concrete mixes over 14-days ponding in 15% NaCl solution were in the range of 5.2 to 9.6 mm when tested at 28 days and 7.4 to 15.2 mm when tested at 182 days. Only in the tests at 182 days, all the ternary concrete mixes had less chloride penetration than the PC control mixes. At 28 days, two of the three ternary mixes containing both silica fume and fly ash had higher chloride penetration than the PC control mix. The ratios of the chloride penetration depths of the ternary mixes to that of the PC mixes were in the range of 0.75 to 1.34 for the tests at 28 days and in the range of 0.72 to 0.92 for the tests at 182 days.

Fig 3.6.3-1 Chloride Penetration in Static Ponding Test: SP(15%) -14d

(in 15% NaCl solution over 14 days from age 28 or 182 days)

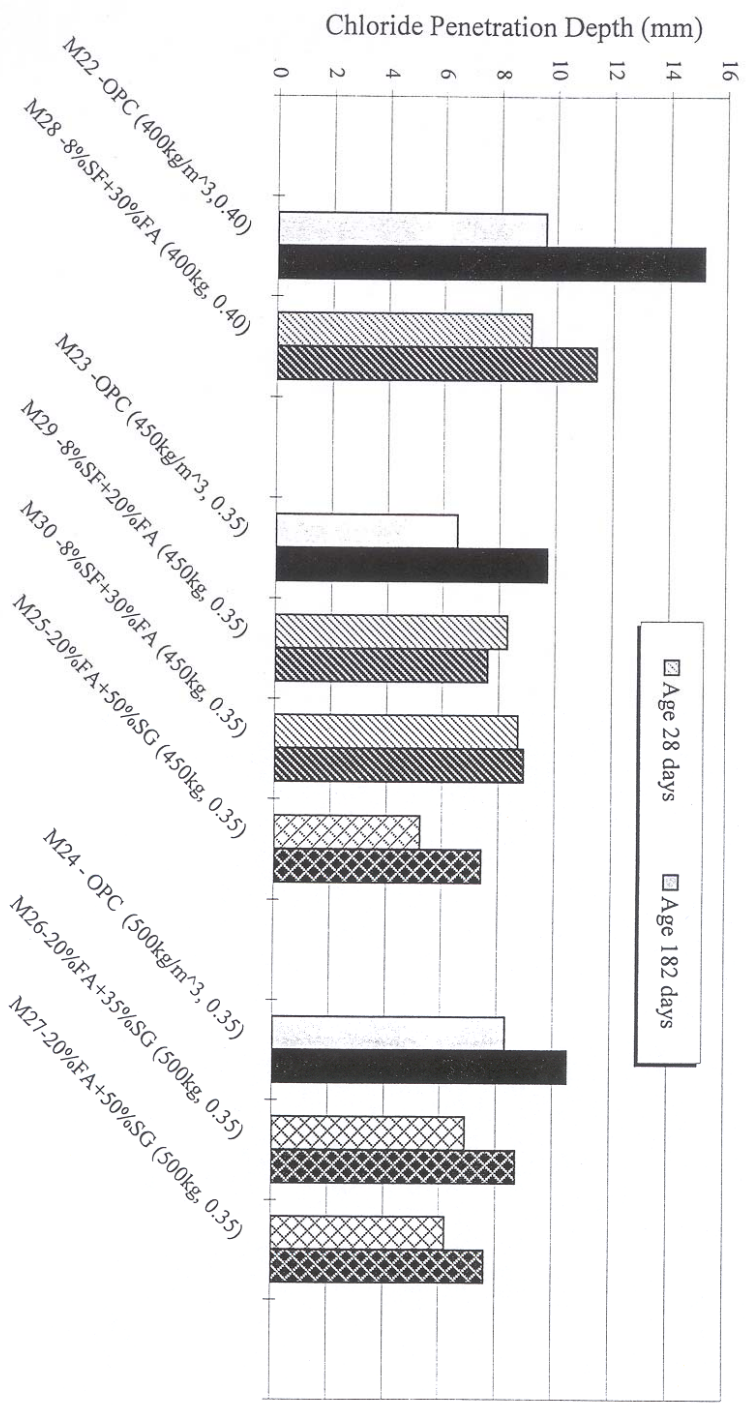


Table 3.6.3-1. Test Results of Static Ponding in 15% NaCl Solution over 14 Days

Mix No.	Binder Type	Binder (kg/m3)	w/b Ratio	At Age 28 Days		At Age 182 Days		Ratio of 182/28D Results
				Chloride Penetration (mm)	Ratio to PC mix	Chloride Penetration (mm)	Ratio to PC mix	
M22	**PC**	400	0.40	**9.6**	**1**	**15.2**	**1**	**1.58**
M 28	8%SF+ 30%FA			9.1	0.95	11.4	0.75	1.25
M 23	**PC**	450	0.35	**6.5**	**1**	**9.7**	**1**	**1.49**
M25	20%FA+ 50%SG			5.2	0.80	7.4	0.76	1.42
M29	8%SF+ 20%FA			8.3	1.28	7.6	0.78	0.92
M30	8%SF+ 30%FA			8.7	1.34	8.9	0.92	1.02
M 24	**PC**	500	0.35	**8.3**	**1**	**10.5**	**1**	**1.27**
M 26	20%FA+ 35%SG			6.9	0.83	8.7	0.83	1.26
M 27	20%FA+ 50%SG			6.2	0.75	7.6	0.72	1.23

PC Concrete

At 28 Days

Comparing the results of M-23 and M-24 with different cement content of 450 and 500 kg/m^3, the richer mix M-24 had higher chloride penetration in the 14-days ponding test. This observation is consistent to that in the BRC binary concrete investigation, in which a continuous increase in chloride penetration was measured in three PC mixes (w/b of 0.40) with the increase in cement content from 350 to 400 and to 450 kg/m^3. However, little effect of cement content on chloride penetration in PC concrete was observed in the 91-days ponding tests in both binary and ternary investigations. It indicates that the effect of cement content on chloride penetration vanishes over the longer ponding duration.

The other PC mix M-22 had lower cement content of 400 kg/m^3 but a higher w/c ratio of 0.40 compared to M-23 and M-24. M-22 recorded higher chloride penetration than M-23 and M-24, which indicated that the w/c ratio had a more significant effect on chloride penetration results than the cement content.

At182 Days

All the three PC mixes had significantly higher chloride penetrations when tested at 182 days over 14-days compared to that tested at 28 days. The aging of specimens in air at 23 °C between 28 to 182 days thus resulted in a higher chloride penetrability in the concrete. The ratio of the results at 182 days to that at 28 days was 1.58, 1.49 and 1.27 for the three PC mixes and was also higher than the ternary mixes in each group with the same binder content and w/b ratio. The ranking in performance of the three PC mixes remained the same as that in the tests at 28 days.

Ternary Concrete Type I: PC +8%SF +(20 or 30)%FA

<u>*At 28 Days*</u>

It was found in the BRC binary concrete investigation that, the ratio of chloride penetrations in a binary mix to the PC mix was 0.60 for the 8% silica fume mix and was 0.98 and 1.30 for the 20% and 30% fly ash mixes. On the other hand, the ratios of results of the three mixes to PC mix in the 91-days tests was 0.43, 0.76 and 0.67. It was found in the binary concrete investigation that, regardless of the NaCl concentration in the solution, the relative chloride penetration ratio of all SCM mixes to the PC mixes decreased with the extension of ponding duration from 14 to 28 and to 91 days.

In the 14-days ponding tests at 28 days in this investigation, two of the three mixes with this ternary binder had higher chloride penetrations than the PC control. The relative chloride penetration ratios of the three ternary mixes compared to the PC mixes were 0.95, 1.28 and 1.34 for M-28, M-29 and M-30 respectively, while that were 0.79, 0.93 and 0.90 for the same three mixes in the 91-days ponding tests.

The mixes M-29 and M-30 contained 20% fly ash and 30% fly ash in the ternary binder with 8% silica fume. Similar to that in the binary concrete investigation, M-30 with a higher fly ash content in the ternary binder recorded a higher chloride penetration than M-29.

The results of the ternary mix M-28 (8%SF +30%FA) was compared to that of two binary mixes, M-7 and M-13, based on the same binder content (400 kg/m^3) and w/b ratio (0.40). M-7 contained 8%SF while M-13 had 30% FA in the binary binder. Table 3.6.3-2 presents the test results of these three mixes and the PC control mix from the tests at the age of 28 days.

Table 3.6.3-2. Comparison of Results of Binary and Ternary Mixes

Mix No.	Binder Type	Binder Content (kg/m^3)	W/b Ratio	Static Ponding (15% NaCl) over 14 Days at Age of 28 Days	
				Chloride Penetration Depth (mm)	Ratio to PC Mix
M22	**PC**	400	0.40	**9.6**	**1**
M-7	8%SF			5.8	0.60
M-13	30%FA			12.5	1.30
M 28	8%SF+30%FA			9.1	0.95

While M-7 and M-13 recorded the chloride penetration depth of 5.8 and 12.5 mm respectively, M-28 had the chloride penetration of 9.1 mm. The ternary mix M-28 in this case had the chloride penetration equal to the average of the two binary mixes.

At182 Days

The age effect on the chloride penetration results over a 14-days ponding was found to be much less significant in the ternary mixes containing both silica fume and fly ash. The results were of little difference at 28 and 182 days for the two ternary mixes M-29 and M-30, although an increase in chloride penetration at 182 days was observed in M-28 with a lower binder content and a higher w/b ratio.

The ratio of the test result at 182 days to that at 28 days was 1.25, 0.92 and 1.02 for M-28, M-29 and M-30 respectively, compared to that of 1.58 and 1.49 for the PC mixes. As the result of more significant increase in chloride penetration in the PC mixes, the relative chloride penetration ratios of the three ternary mixes to the PC mixes reduced from 0.95, 1.28 and 1.34 at 28 days to 0.75, 0.78 and 0.92 at 182 days.

Ternary Concrete Type II: PC +20%FA +(35 or 50)%Slag

At 28 Days

In the BRC binary concrete investigation, the ratio of chloride penetrations of a binary mix to the PC mix was 0.98 for the 20% fly ash mix and was 0.68 and 0.57 for the 35% and 50% slag mixes. These binary concrete mixes had the binder content of 400 kg/m^3 and w/b ratio of 0.40.

Three mixes containing 20%FA plus 35% or 50% slag in the ternary binder were investigated in this project. However, they had different binder content or w/b ratio compared to the above binary mixes with fly ash or slag. Therefore, the test results were not directly comparable to that of these binary mixes.

In this investigation, the three ternary mixes all had lower chloride penetrations than the PC mixes. The ratio of the test results of the three ternary mixes to the PC mix was 0.80, 0.83 and 0.75 for M-25, M-26 and M-27 respectively.

Within the group with the binder content of 450 kg/m^3 and w/b of 0.35 (see Table 3.6.3-1), M-25 (20%FA +50%Slag) had a lower chloride penetration than the other two ternary mixes (M-29 and M-30) containing SF +FA.

For the two mixes with different slag contents, the mix with higher slag content, M-27 (20%FA +50%Slag), recorded a slightly lower chloride penetration than M-26 (20%FA +35%Slag). This result was similar to that in the binary concrete tests, in which the increase of slag content from 35% to 50% in the binary binder resulted in lower chloride penetration.

At 182 Days

The effect of specimen aging in air on the chloride penetration results of the ternary mixes with both fly ash and slag was slightly less significant than that in the PC mixes but more significant than that in the ternary mixes containing silica fume and fly ash.

The ratio of the test result at 182 days to that at 28 days was 1.42, 1.26 and 1.23 for M-25, M-26 and M-27 respectively. The relative chloride penetration ratios of the three ternary mixes to the PC mixes were only slightly lower at 182 days than that at 28 days.

3.6.4 CYCLIC PONDING IN 15% NaCl SOLUTION OVER 14 DAYS

This test has been developed at the BRC in order to accelerate chloride penetration and to reduce the test duration by using a high concentration NaCl (15%) solution and the wet-and-dry test procedure.

Salt-water ponding tests with wetting and drying cycles closely simulate the conditions that exist in the splash or tidal zones of marine environments. During the wetting period, salt water penetrates into the concrete by capillary action. During drying, the water is drawn out of the concrete, leaving the salt in the matrix. This results in the accumulation of a higher concentration of chlorides and leads to the acceleration of chloride penetration into the concrete.

In this research program, the cyclic ponding test was carried out for all the nine mixes over 14 days consisting of 14 cycles of 12-hour immersion at room temperature and 12-hour drying at 40 °C. In order to compare the effects of specimen age on the test results two tests were conducted for each mix and commenced at the concrete age of 28 and 182 days respectively.

The size and curing regime of the specimens were the same as that in the 14-days static ponding test. The specimens were moist cured in moulds for one day, followed by lime-water curing to 7 days, then air-cured at 23 °C until commencement of immersion test at 28 days or 182 days. The water-soluble chloride penetration depth in a specimen was also determined in the same way as that in the static ponding tests.

Table 3.6.4-1 and Fig 3.6.4-1 present the results of chloride penetration of all the nine concrete mixes tested at 28 days and at 182 days. The nine mixes were divided into three groups according to binder content and w/b ratio.

Overall, the chloride penetration in concrete over the 14-days cyclic ponding test was higher than that in the 14-days static ponding test. The range of chloride penetration depths in the cyclic test was from 6.8 to 12.0 mm at 28 days and 7.4 to 18.4 mm at 182 days, while that in the static test was from 6.2 to 9.6 mm and 7.4 to 15.2 mm respectively.

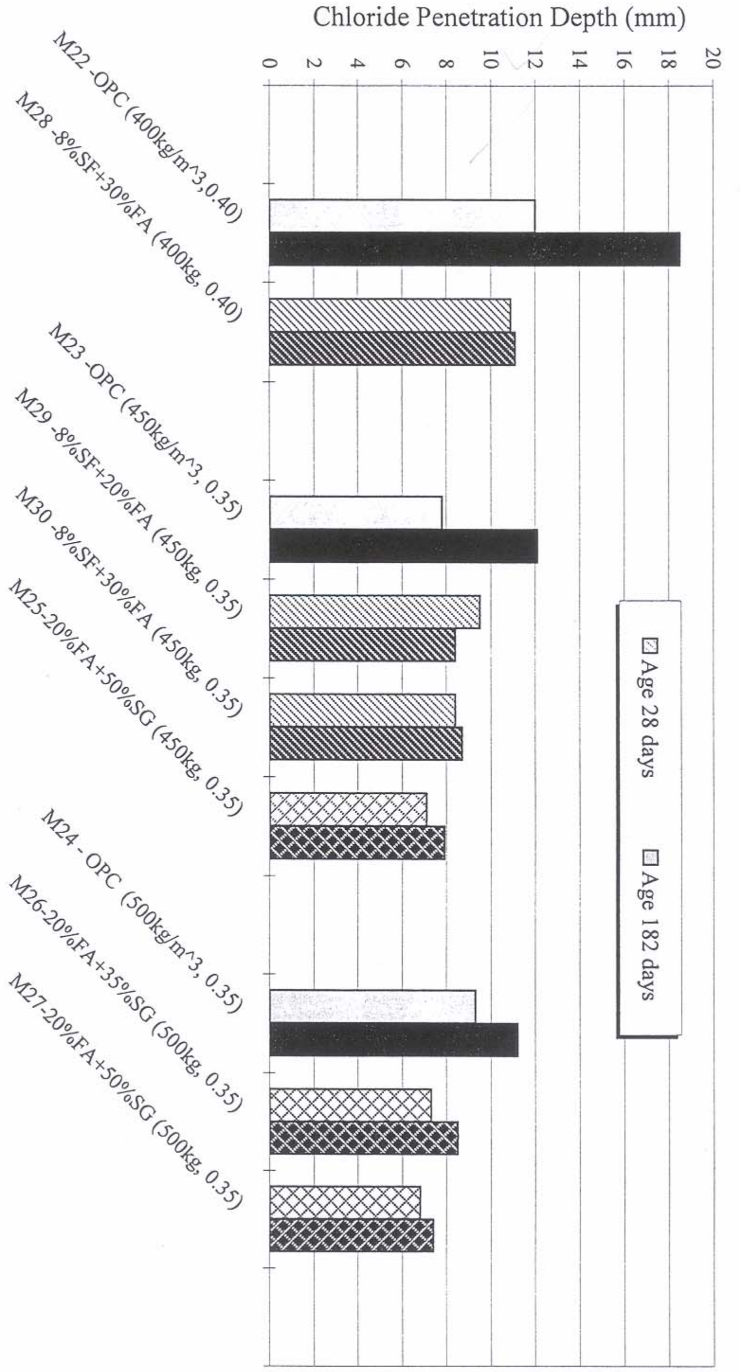


Fig 3.6.4-1 Chloride Penetration in Cyclic Ponding Test: CP(15%) -14d
(using 15% NaCl solution over 14 days from age 28 or 182 days)

Table 3.6.4-1. Test Results of 14-Days Cyclic Ponding in 15% NaCl Solution

Mix No.	Binder Type	Binder (kg/m3)	w/b Ratio	At Age 28 Days		At Age 182 Days		Ratio of 182/28D Results
				Chloride Penetration (mm)	Ratio to PC mix	Chloride Penetration (mm)	Ratio to PC mix	
M22	**PC**	400	0.40	**12.0**	**1**	**18.4**	**1**	**1.54**
M 28	8%SF+ 30%FA			10.9	0.91	11.1	0.60	1.02
M 23	**PC**	450	0.35	**7.8**	**1**	**12.1**	**1**	**1.55**
M25	20%FA+ 50%SG			7.1	0.91	7.9	0.65	1.11
M29	8%SF+ 20%FA			9.5	1.22	8.4	0.69	0.88
M30	8%SF+ 30%FA			8.4	1.08	8.7	0.72	1.04
M 24	**PC**	500	0.35	**9.3**	**1**	**11.2**	**1**	**1.20**
M 26	20%FA+ 35%SG			7.3	0.78	8.5	0.76	1.16
M 27	20%FA+ 50%SG			6.8	0.73	7.4	0.66	1.09

However, the increase in chloride penetration in the cyclic ponding test was more significant in the PC mixes than in the ternary mixes. Therefore, the relative chloride penetration ratios of all the ternary mixes in relation to the PC mixes were lower in the cyclic ponding test compared to that in the static ponding test. The relative chloride penetration ratios of the ternary mixes were in the ranges from 0.73 to 1.22 at 28 days and from 0.60 to 0.76 at 182 days, comparing to those in the static ponding test from 0.75 to 1.34 and from 0.72 to 0.92 respectively.

Similar to that in the 14-days static ponding test, all the ternary concrete mixes, except for the two (M-29 and M-30) tested at 28 days, had less chloride penetration than the PC control mixes in the cyclic ponding test.

PC Concrete

At 28 Days

The chloride penetrations in the three PC mixes were higher in the cyclic ponding test than that in the static ponding test over the same period of 14 days.

In the BRC binary concrete investigation, a slightly decrease in chloride penetration was measured in three PC mixes (w/b of 0.40) with the increase in cement content from 350 to 400 and to 450 kg/m^3.

In this investigation, M-23 and M-24 had the same w/c ratio of 0.35 but different cement content of 450 and 500 kg/m^3. The richer mix M-24 had a slightly higher chloride penetration in the cyclic ponding test at 28 days.

Another PC mix M-22 had lower cement content of 400 kg/m^3 but a higher w/c ratio of 0.40 compared to M-23 and M-24. M-22 recorded much higher chloride penetration than M-23 and M-24, which indicated that the w/c ratio had a more significant effect on chloride penetration results than the cement content.

At182 Days

All the three PC mixes had significantly higher chloride penetrations in the cyclic ponding test at 182 days than that at 28 days. Similar to that in the static ponding test, the aging of specimens in air at 23 °C between 28 to 182 days resulted in higher chloride penetrability in PC concrete. The ratio of the results at 182 days to that at 28 days was 1.54, 1.55 and 1.20 for the three PC mixes. Less increase in chloride penetration due to aging in air was observed in the mix M-24 which had the highest cement content of 500 kg/m^3. The richer mix M-24 also had a slightly lower chloride penetration than the leaner mix M-23 when tested at 182 days.

Ternary Concrete Type I: PC +8%SF +(20 or 30)%FA

At 28 Days

It was found in the BRC binary concrete investigation, the chloride penetration in the cyclic ponding test at 28 days was significantly increased in PC and silica fume concrete, slightly increased in slag concrete but slightly reduced in fly ash concrete, comparing to that in the static ponding test. Thus, the relative chloride penetration of the binary concrete to PC concrete in the cyclic test was increased slightly for silica fume concrete, but reduced slightly for slag concrete and reduced significantly for fly ash concrete. The relative chloride penetration ratios of the five binary fly ash mixes reduced from the range of 0.98-1.43 in the static ponding test to the range of 0.78-1.04 in the cyclic ponding test.

In the cyclic ponding test at 28 days of this investigation, two of the three ternary mixes with silica fume and fly ash had higher chloride penetrations than the PC control. The relative chloride penetration ratios of the three ternary mixes were 0.91, 1.22 and 1.08 for M-28, M-29 and M-30 respectively. These ratios were however lower than that in the static ponding test, especially for the mix M-30.

The mixes M-29 and M-30 both contained 8% silica fume but 20% fly ash and 30% fly ash respectively. Similar to the results of binary mixes with 20% and 30% fly ash, M-30 with 30% fly ash in the ternary binder recorded more significant reduction in the relative chloride penetration ratio in the cyclic test compared to that in the static ponding test. However, the results of M-29 and M-30 are not directly comparable to that of the binary mixes with 20% and 30% fly ash because they had different binder contents and w/b ratios.

The result of the ternary mix M-28 (8%SF +30%FA) was comparable to that of two binary mixes M-7 and M-13, based on the same binder content (400 kg/m^3) and w/b ratio (0.40). M-7 contained 8%SF while M-13 had 30% FA in the binary binder. Table 3.6.4-2 presents the test results of these three mixes and the PC control mix from the cyclic ponding tests at the age of 28 and 182 days.

Table 3.6.4-2. Results of Binary and Ternary Mixes in Cyclic Ponding Test

Mix No.	Binder Type	Binder (kg/m3)	w/b Ratio	At Age 28 Days		At Age 182 Days		Ratio of 182/28D Results
				Chloride Penetration (mm)	Ratio to PC mix	Chloride Penetration (mm)	Ratio to PC mix	
M22	**PC**	400	0.40	**12.0**	**1**	**18.4**	**1**	**1.54**
M-7	8%SF			7.4	0.62	16.3	0.89	2.20
M-13	30%FA			11.3	0.94	12.1	0.66	1.09
M 28	8%SF+30%FA			10.9	0.91	11.1	0.60	1.02

While M-7 and M-13 recorded the relative chloride penetration ratios of 0.62 and 0.94, M-28 had this ratio of 0.91. The ternary mix M-28 had the chloride penetration between that of the two binary mixes but the result was very close to that of the binary mix with 30% fly ash only.

<u>*At182 Days*</u>

In the binary concrete investigation, PC concrete and binary concrete containing silica fume, fly ash or slag were all found to have higher chloride penetration when tested at 182 days than at 28 days. As shown in Table 3.6.4-2, the ratio of chloride penetration depth at 182 days compared to that at 28 days was 1.54 for the PC mix, 2.20 for the 8% silica fume mix and 1.09 for the 30% fly ash mix. Particularly, the binary concrete with silica fume had very significant increase in chloride penetration when stored in air at 23 °C after the first seven days lime-water curing and tested at 182 days. Some possible reasons for such performance of silica fume concrete have been discussed in the report on the BRC binary concrete investigation (Chang et. al, 1998).

In the cyclic ponding tests of this investigation, the age effect on chloride penetration was found to be much less significant in the ternary mixes containing both silica fume and fly ash. Comparing the results in Table 3.6.4-2 based on the same binder content and w/b ratio, the age effect of the ternary mix M-28 was negligible and much less significant than the binary silica fume mix M-7. It indicated that the degradation in the performance of silica fume concrete with aging in air could be improved by the use of ternary binder containing fly ash as well.

While the results were also of little difference at 28 and 182 days for the ternary mix M-30, there was a decrease in chloride penetration at 182 days for M-29.

The ratio of the test result at 182 days to that at 28 days was 1.02, 0.88 and 1.04 for M-28, M-29 and M-30 respectively, compared to that of 1.54 and 1.55 for the PC control mixes. As the result of the much greater increase in chloride penetration in the PC mixes at 182 days, the relative chloride penetration ratios of the three ternary mixes reduced from 0.91, 1.22 and 1.08 at 28 days to 0.60, 0.69 and 0.72 at 182 days.

Ternary Concrete Type II: PC +20%FA +(35 or 50)%Slag

At 28 Days

In the BRC binary concrete investigation, the ratio of chloride penetrations of a binary mix to the PC mix was 0.85 for the 20% fly ash mix and was 0.63 and 0.44 for the 35% and 50% slag mixes. These binary concrete mixes had the binder content of 400 kg/m^3 and w/b ratio of 0.40.

Three mixes containing 20%FA plus 35% or 50% slag in the ternary binder were investigated in this project. However, they had a higher binder content (450 kg/m^3) and a lower w/b ratio (0.35) compared to the above binary mixes. Therefore, the test results were not directly comparable to that of these binary mixes.

In this investigation, the three ternary mixes all had lower chloride penetrations than the PC mixes. The ratio of the test results of the three ternary mixes to the PC mix was 0.91, 0.78 and 0.73 for M-25, M-26 and M-27 respectively.

Within the group with the binder content of 450 kg/m^3 and w/b of 0.35 (see Table 3.6.4-1), M-25 (20%FA +50%Slag) had a lower chloride penetration than the other two ternary mixes (M-29 and M-30) containing SF +FA.

For the two mixes with different slag contents, the mix with higher slag content, M-27 (20%FA +50%Slag), recorded a slightly lower chloride penetration than M-26 (20%FA +35%Slag). This trend was the same as that in the binary concrete tests, however, more significant reduction in chloride penetration was observed with the increase of slag content from 35% to 50% in the binary binder.

At 182 Days

The effect of specimen age on the chloride penetration results of the ternary mixes with both fly ash and slag was less significant than that in the PC mixes but slightly more significant than that in the ternary mixes containing silica fume and fly ash (Table 3.6.4-1 and Fig 3.4.6-1).

The ratio of the test result at 182 days to that at 28 days was 1.11, 1.16 and 1.09 for M-25, M-26 and M-27 respectively, compared to that of 1.55 and 1.20 for the PC control mixes. Due to the greater increase in chloride penetration in the PC mixes at 182 days, the relative chloride penetration ratios of the three ternary mixes reduced from 0.91, 0.78 and 0.73 at 28 days to 0.65, 0.76 and 0.66 at 182 days.

3.6.5 COMPARISON OF CHLORIDE PENETRATION TEST RESULTS

All the nine concrete mixes in this investigation were tested with seven chloride penetration tests based on the following four test methods:

- "the six-hours rapid chloride permeability test (ASTM C1202) at age 28 and 182 days”
- “3% NaCl static ponding test at age 28 days over 91 days”
- “15% NaCl static ponding test over 14 days at age 28 and 182 days"
- “15% NaCl cyclic ponding test over 14 days at age 28 and 182 days"

Performances of Ternary Concrete Mixes in Seven Chloride Penetration Tests

Table 3.6.5-1 presents the overall ranges of the relative chloride penetration ratios of the ternary mixes to their PC control mix in each of the seven tests.

Table 3.6.5-1. Relative Chloride Penetration in Ternary and PC concrete

Test Method	3 PC mixes	3 Ternary Mixes (SF+FA)	3 Ternary Mixes (FA+SG)
ASTM C1202-28d	1	0.37 – 0.44	0.32 – 0.47
ASTM C1202-182d	1	0.10 – 0.14	0.15 – 0.17
SP(3%)28d-91d	1	0.79 – 0.93	0.76 – 0.83
SP(15%)28d-14d	1	0.95 – 1.34	0.75 – 0.83
SP(15%)182-14d	1	0.75 – 0.92	0.72 – 0.83
CP(15%)28d-14d	1	0.91 – 1.22	0.73 – 0.91
CP(15%)182d-14d	1	0.60 – 0.72	0.65 – 0.76

Note: ASTM C1202-28d = Rapid Chloride Permeability test at age 28 Days

SP(3%)28d-91d = Static Ponding test in 3% NaCl solution at age 28 Day over 91 Days

CP(15%)28d-14d = Cyclic Ponding test in 15% NaCl solution at age 28 Day over 14 Days

Similar explanations apply to the other tests

In general, the range of relative chloride penetration in Table 3.6.5-1 indicated that the two types of ternary mixes had similar performance in five of the seven tests. In the 14-days static and cyclic ponding tests at 28 days, however, the ternary mixes with fly ash and slag had obviously better performance than the ternary mixes with silica fume and fly ash. At later age of 182 days, both types of ternary concrete recorded very similar performance in the same two tests.

Comparing to the PC control mixes, the ternary mixes containing fly ash and slag had better performance in all the seven chloride penetration tests. In five of the seven tests the ternary mixes with silica fume and fly ash performed better than the PC mixes, while two of the three such ternary mixes recorded higher chloride penetrations in the 14-days static and cyclic ponding tests at 28 days.

The relative performance levels of either type of ternary concrete compared to the PC concrete varied with the test methods and the specimen ages.

The performances of all the ternary mixes in the ASTM C1202 tests were remarkably superior to that of the PC concrete. The ratios of coulomb values of the ternary mixes to the PC mixes were in the range of 0.32 to 0.47 at age 28 days and of 0.10 to 0.17 at 182 days. There was little difference in the performance of the two types of ternary mixes in the ASTM C1202 test. For comparison to the results of binary concrete, Table 3.6.5-2 presents the relative chloride penetration ratios of those binary concrete mixes which contained 8% silica fume, 20% to 30% fly ash or 35% to 50% slag in the binder.

Table 3.6.5-2. Relative Chloride Penetration in Some Binary Mixes

Test Method	**5 PC mixes**	**8% Silica Fume (4 mixes)**	**20-30% Fly Ash (4 mixes)**	**35-50% Slag (3 mixes)**
ASTM C1202-28d	1	0.24 – 0.46	0.59 – 0.93	0.36 – 0.45
ASTM C1202-182d	1 (one mix)	0.30 (one mix)	0.12-0.21 (2 mix)	0.32-0.44 (2 mix)
SP(3%)28d-91d	1	0.39 – 0.68	0.67 – 0.81	0.41 – 0.55
SP(15%)28d-14d	1	0.59 – 0.74	0.98 – 1.30	0.57 – 0.68
SP(15%)182d-14d	N/A	N/A	N/A	N/A
CP(15%)28d-14d	1	0.62 – 0.76	0.78 – 1.04	0.44 – 0.63
CP(15%)182d-14d	1 (one mix)	0.89 (one mix)	0.66 (one mix)	0.47 (one mix)

In the ASTM C1202 test at 28 days, the coulomb values of the two types of ternary concretes were similar to that of the silica fume and slag binary concrete respectively, but much lower than that of the fly ash concrete. At 182 days, however, the results of both ternary concretes were very close to that of the fly ash binary concrete and much lower than that of the silica fume and slag binary concrete. The effects of fly ash in the ternary binders on the ASTM C1202 test results were much more significant at 182 days than at 28 days. Therefore, the ternary concrete with fly ash and silica fume or slag had achieved very low coulomb values at both 28 and 182 days. However, whether the ASTM C1202 tests results can be directly related to the resistance of various concrete mixes to chloride penetration is questionable and needs further investigations.

The superior relative performance of the ternary mixes to the PC mixes were much less pronounced in the static or cyclic chloride ponding tests. The two types of ternary binders also had different performances in these tests, while their performances in the ASTM C1202 test were similar.

For the ternary mixes with both fly ash and slag in the binder, quite stable performance was observed in different static and cyclic ponding tests (Table 3.6.5-1). The relative chloride penetrations in these ternary mixes were from 0.72 to 0.83 in the static ponding tests and were from 0.65 to 0.91 in the cyclic ponding tests at the ages of 28 and 182 days. While the effect of specimen aging in air had little effect on the 14-days static ponding test results, the age effect was a bit more significant in the cyclic ponding test. The ternary mix with fly ash and slag had improved relative performance in the cyclic ponding test when tested at the latter age of 182 days.

In the BRC binary concrete investigation, the slag concrete was also found to have quite stable performance in different static and cyclic ponding tests (Table 3.6.5-2). The ternary mixes with both slag and fly ash, in most cases, had the relative chloride penetration ratios between that of the slag and fly ash binary mixes. In the 91-days 3% NaCl static ponding test, however, this type of ternary concrete were found to perform more close to the fly ash binary concrete rather than the slag binary concrete.

For the ternary mixes with both silica fume and fly ash, their performances in the static and cyclic ponding tests were generally poorer than that of the ternary mixes with fly ash and slag. Effect of specimen age was significant for the ternary concrete with silica fume and fly ash and improved performance was achieved when specimens were tested at the latter age of 182 days in both static and cyclic tests. While two of the three such mixes even had higher chloride penetrations than the PC controls at 28-days, all the three mixes had lower penetration than the PC mixes at 182 days.

Comparing to the results of binary concrete in the static and cyclic ponding tests, the ternary concrete with silica fume and fly ash generally had similar or poorer relative performance than the binary concrete. In most cases, the ternary mixes of this type had much higher chloride penetration than the silica fume concrete and had similar or slightly higher chloride penetration than the fly ash concrete. However, this ternary concrete recorded lower chloride penetration than the silica fume concrete in the cyclic ponding test at 182 days. It was found in the binary concrete investigation that chloride penetration in the silica fume concrete increased significantly in the cyclic ponding test at 182 days compared to that at 28 days. It appeared that this degradation in performance of silica fume concrete with aging in air could be improved by addition of fly ash in silica fume concrete.

The effect of specimen age on chloride penetration in both of the static and cyclic ponding tests was also found to be opposite to that on coulomb value in the ASTM C1202 test. While much lower electrical charges were measured at 182 days compared to that at 28 days for all the mixes, higher chloride penetration depths were measured at 182 days compared to that at 28 days. The curing regimes were different for these tests. The specimens for the ASTM test were continuously cured in lime-water and those for ponding tests were air-cured after initial 7-days lime-water curing. However, the curing regime was not necessary to be the only reason for the different age-effects in these tests.

In the research work by Pigeon et al (Pigeon et al, 1993), the results of the ASTM C1202 test were compared between concrete specimens dried at 23 °C for additional 28 and 90 days after initial 7 days of moist curing. Four binders were investigated including a normal portland cement, a high early strength cement and two binary binders containing 10% silica fume in each of the two cements. The results of all the concrete mixes indicated that the coulomb values decreased with the increased drying periods of 0, 28 and 90 days after the initial 7 days moist curing.

Overall, the seven chloride tests can be classified into two groups based on the significant differences in the relative performance of the ternary concrete mixes to the PC mixes in the tests. One group consists of the two ASTM C1202 tests at 28 or 182 days and the other group consists of the five static or cyclic ponding tests.

In the ASTM C1202 test, the two types of ternary concrete had similar performance. The ratios of the coulomb values of the ternary concretes to the PC concrete were very low (0.32 to 0.47) at 28-days and even lower (0.10 to 0.17) at 182-days.

However, in the static or cyclic ponding tests, the relative chloride penetration ratios of the two types of ternary concrete were much higher than that indicated in the ASTM C1202 tests. The two types of ternary concrete also had some different performances in the static or cyclic ponding tests. The ternary concrete with slag and fly ash had better performance than the PC concrete but only with the relative chloride penetration ratios in the range of 0.65 to 0.91. On the other hand, the ternary concrete with silica fume and fly ash only had better performance than the PC concrete in the tests at 182-days or at 28-days over 91 days. In the 14 days static and cyclic ponding tests at 28 days, two of three ternary mixes with silica fume and fly ash had higher chloride penetration than the PC controls.

The differences between the results of the ASTM C1202 test and the static or cyclic ponding tests were also found to be more pronounced in the ternary concretes than that in the binary concretes. The fly ash in the ternary concretes appeared to have different behaviours in the ASTM C1202 test and the chloride ponding tests. In the ASTM C1202 test, the addition of fly ash in the ternary binder did not affect the low coulomb value at 28 days of a silica fume or slag concrete. On the other hand, the fly ash addition had a significant effect on the lower coulomb values at 182 days in the ternary concrete containing either silica fume or slag. In the static or cyclic tests, however, the fly ash in the ternary binder resulted in higher chloride penetrations in most cases, compared to that of the slag and silica fume binary concrete. Only in the cyclic ponding test at 182 days, the fly ash in the ternary binder effectively reduced the high chloride penetration of silica fume binary concrete at the latter age.

The effect of specimen testing age on chloride penetration in both of the static and cyclic ponding tests was also found to be opposite to that on coulomb value in the ASTM C1202 test. While specimen curing condition in this program was different in the ASTM C1202 test and the ponding tests, it was not the sole reason for the different age effects, since other research work had shown the reduction in coulomb value with air-dry aging.

Correlations between the Results of Seven Chloride Penetration Tests

The correlation coefficients between the test results of the seven chloride penetration tests were calculated on statistic basis. Table 3.6.5-3 gives the correlation coefficients based on the test results of the nine concrete mixes with ternary or PC binders.

Table 3.6.5-3. Correlation Coefficients between Chloride Tests

	ASTM C1202-28d	ASTM C1202-182d	SP(3%) 28d-91d	SP(15%) 28d-14d	SP(15%) 182d-14d	CP(15%) 28d-14d	CP(15%) 182d-14d
ASTM C1202-28d	1	0.96	0.79	0.35	0.73	0.48	0.79
ASTM C1202-182d		1	0.73	0.21	0.64	0.37	0.76
SP(3%)28d-91d			1	0.72	0.96	0.88	0.97
SP(15%)28d-14d				1	0.70	0.89	0.59
SP(15%)182d-14d					1	0.84	0.96
CP(15%)28d-14d						1	0.78
CP(15%)182d-14d							1

There are twenty-one combinations among the seven chloride penetration tests for the correlation analysis between the results of two tests. The twenty-one calculated correlation coefficients in Table 3.6.6-2 are in the range from 0.21 to 0.97.

The results of the ASTM C1202 test at age 28 days had correlation coefficients with that of the other six tests in the range of 0.35 to 0.96 and had the best correlation with the results of the same test method at age 182 days. Moderate but not strong correlations, indicated by the correlation coefficients of 0.73 to 0.79, were observed between the ASTM C1202-28d and the static or cyclic ponding tests at 182 days as well as the 91-days ponding test from 28-days. Poor correlations were found between the ASTM C1202-28d test and the static or cyclic ponding tests at 28 days.

There were very good correlations among the static or cyclic ponding tests (15%NaCl) at 182 days and the 91-days ponding test (3%NaCl) from 28-days with the correlation coefficients of 0.96, 0.96 and 0.97.

The cyclic ponding (15%NaCl) test at 28 days over 14 days had moderate to fairly good correlations (coefficients of 0.78, 0.84, 0.88 and 0.89) with the other ponding tests, but had poor correlations with the ASTM C1202 tests (coefficients of 0.37 and 0.48). The static ponding (15%NaCl) test at 28 days over 14 days had weaker correlations with other six tests than the cyclic ponding test at 28 days.

In general, the results of correlation analyses also indicated the significant difference between the two groups of tests, the two ASTM C1202 tests and the five static or cyclic ponding tests. The correlation coefficient between two tests with in a group was much higher than that of two tests of different groups. The three chloride ponding tests at the latter age of 182 days or over 91-days from 28 days correlated very well. The cyclic ponding test at 28 days also had the second best correlations with these three tests (coefficients of 0.78, 0.84 and 0.88). The static ponding test at 28 days had a bit weaker correlations with other tests than the cyclic ponding test.

Correlation between Compressive Strength and Chloride Penetration Results

The correlation coefficients between the 3-day, 28-day and 91-day compressive strengths and the results of the seven chloride penetration tests are presented in Table 3.6.5-4.

Table 3.6.5-4. Correlation Coefficients between Strength and Chloride Tests

Compressive Strength	ASTM C1202-28d	ASTM C1202-182d	SP(3%) 28d-91d	SP(15%) 28d-14d	SP(15%) 182d-14d	CP(15%) 28d-14d	CP(15%) 182d-14d
3-Day	0.79	0.82	0.51	0.31	0.34	0.25	0.46
28-Day	0.26	0.29	-0.09	0.02	-0.22	-0.26	-0.13
91-Day	-0.02	-0.03	-0.41	-0.24	-0.43	-0.53	-0.41

In general, very poor correlations were found between the results of all the seven chloride tests and the compressive strengths at 3, 28 or 91 days. The correlation coefficients of 0.79 and 0.82 seem to indicate moderate correlations between the 3-day compressive strength and the two ASTM C1202 tests. However, this correlation between the 3-day strength and either of the ASTM C1202 results was opposite to what one expected. In fact, these positive correlation coefficients meant that the higher the 3-day compressive strength, the higher the coulomb value or higher chloride permeability as well.

As shown in Table 3.6.5-4, the compressive strengths at different ages also had significantly altered correlations with the results of chloride penetration tests. The all-positive correlation coefficients between the results of chloride tests and the 3-day compressive strengths indicated that the concrete mixes with higher 3-day strengths (mostly PC mixes) also had higher chloride penetration. The 28-day compressive strengths generally bore no significant correlations at all to all the chloride tests for the mixes in this investigation. The negative correlation coefficients between the 91-day strengths and the chloride tests were also very low, however, at the least the trend of the correlations was a higher strength relating to a lower chloride penetration.

In the BRC binary concrete investigation, the correlations between the compressive strengths and the results of chloride tests were much better than that in this ternary concrete investigation. Table 3.6.5-5 gives the correlation coefficients between the strengths and the results in four identical chloride tests of twenty-one mixes in the binary concrete investigation.

Table 3.6.5-5. Correlation Coefficients in Binary Concrete Investigation

Compressive Strength	ASTM C1202-28d	ASTM C1202-182d	SP(3%) 28d-91d	SP(15%) 28d-14d	SP(15%) 182d-14d	CP(15%) 28d-14d	CP(15%) 182d-14d
3-Day	-0.18	N/A	-0.04	-0.60	N/A	-0.13	N/A
28-Day	-0.60	N/A	-0.53	-0.87	N/A	-0.65	N/A
91-Day	-0.66	N/A	-0.65	-0.80	N/A	-0.73	N/A

The following factors may be counted as part of the reasons for the better correlations, though not strong, between the strengths and chloride tests in the binary concretes. Firstly, the total percentage contents of the SCMs in the ternary binders were higher than that in the binary binders with the same SCMs. Secondly, the total binder contents were also higher in the ternary mixes than in most binary mixes. Thirdly, while the ternary mixes had higher strength than the PC controls only in 2 out of 18 compressive tests, the binary mixes achieved higher strength than the PC mixes in 28 out of 48 tests. Since both binary and ternary mixes had lower chloride penetrations than the PC mixes in most cases, better correlations between the strengths and chloride tests, higher strengths accompanied with lower chloride penetrations, of the binary concrete tests could be expected. Fourthly and not necessary the last, the statistic sample size in the ternary program (9 mixes) was much smaller than that in the binary program (21 mixes), which could also have some influence on the analytical correlation results.

In conclusion, while it was found in the binary concrete investigation that compressive strength did not have good correlation with the resistance to chloride penetration, the current ternary concrete investigation further revealed that this correlation would be even worse in concrete with higher percentages and two SCMs in the binder.

3.7 WATER ABSORPTION

The water absorption test in this program was based on ASTM C642 with modified pre-conditioning procedures. ASTM C642 requires the specimens to be oven-dried at 100 to 110 °C to a constant weight before being immersed in water. There was, however, a concern that this oven-dry procedure may have different effects on the various binary binder systems. It was then recommended by the project steering committee to precondition the specimens, after an initial 7 days lime-water curing, at 23 °C and 55±10% R.H. until the time of immersion at the age of 28 days.

However, it was found in the BRC binary concrete investigation that the measured water absorption percentages were very low based on the above air-drying precondition procedure and the results had poor correlations with the chloride penetration tests. These might be due to relatively high and varied moisture contents in the specimens of different concrete mixes before the specimens were immersed in water.

Therefore, it was decided to measure the Oven-dry water absorption as well in the ternary concrete investigation. After the Air-dry water absorption at 28 days was measured, the specimens were put in an oven at 105 °C over three days and their over-dry weights were measured. The Oven-dry water absorption was then determined by the difference of the oven-dry weight (W3) and the SSD weight (W2) of a specimen divided by W2 and expressed in percentage.

The specimens were stored in the temperature-controlled room at 23 ± 1 °C and 55 ± 15% RH after the above 28-day water absorption tests. At the age of 182 days, the same specimens were also used to measure their Oven-dry water absorption and the results were compared with that at 28 days. All the nine concrete mixes were investigated in this way on their water absorption performance at 28 and 182 days. Since the use of the same specimens for the water absorption tests at 182 days was not a rational approach, the test results from this arrangement might only be used for evaluation of the effects of test ages under the specific conditions.

Fig 3.7-1 and Table 3.7-1 present the water absorption results at 28 days after the specimens being air-dried and oven-dried. Fig 3.7-2 and Table 3.7.2 compare the water absorption results with oven-dried specimens at 28 day and 182 days.

Table 3.7-1. Water Absorption Test Results at 28 Days

Mix No.	Binder Type	Binder (kg/m^3)	w/b Ratio	**(I) Sample Air-Dried**		**(II) Sample Oven-Dried**		**Ratio of Results II / I**
				Water Absorption (%)	Ratio to PC mix	Water Absorption (%)	Ratio to PC mix	
M22	**PC**	400	0.40	**0.87**	**1**	**4.65**	**1**	**5.3**
M 28	8%SF+ 30%FA			1.61	1.85	3.71	0.80	2.3
M 23	**PC**	450	0.35	**0.43**	**1**	**3.88**	**1**	**9.0**
M25	20%FA+ 50%SG			0.96	2.23	3.21	0.83	3.3
M29	8%SF+ 20%FA			0.81	1.88	3.61	0.93	4.5
M30	8%SF+ 30%FA			1.00	2.33	3.23	0.83	3.2
M 24	**PC**	500	0.35	**0.48**	**1**	**4.30**	**1**	**9.0**
M 26	20%FA+ 35%SG			1.09	2.27	3.73	0.87	3.4
M 27	20%FA+ 50%SG			0.92	1.92	3.34	0.78	3.6

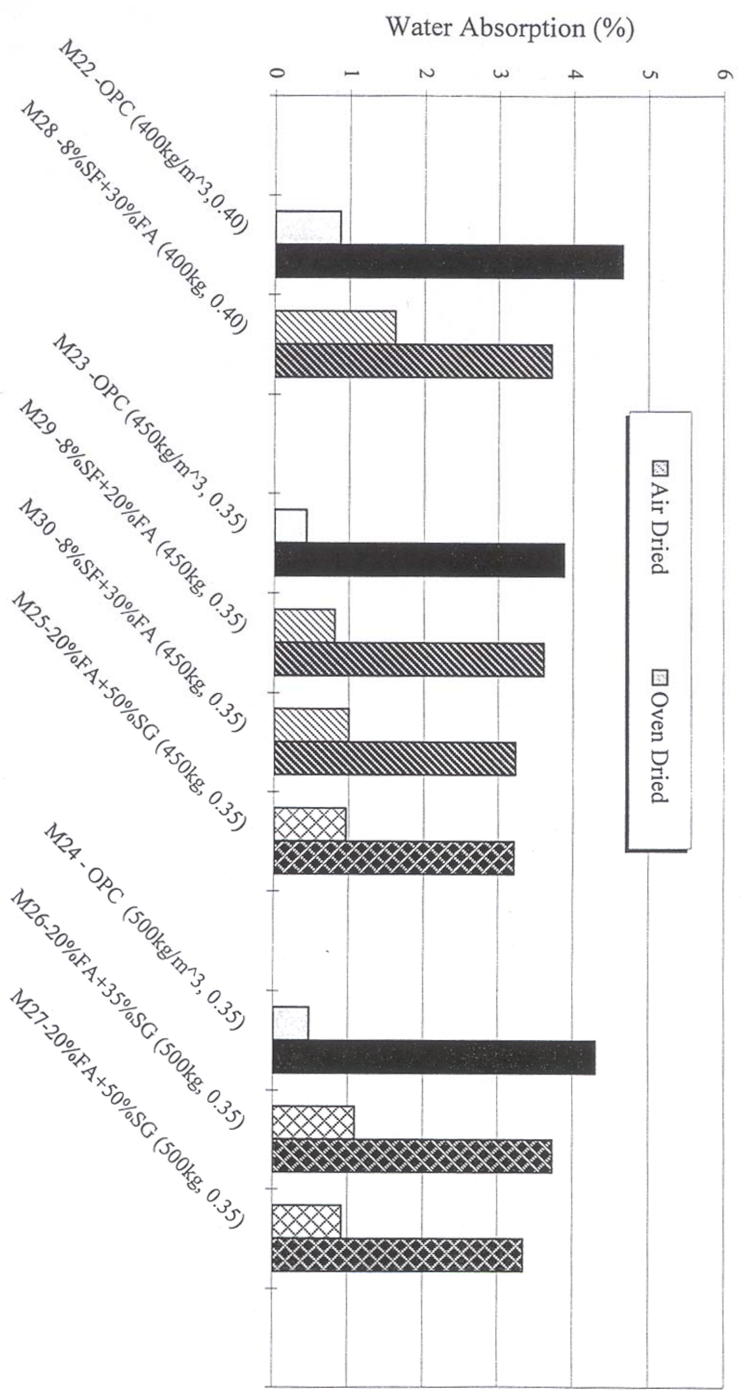


Fig 3.7-1 Water Absorption Results Tested at Age 28 Days

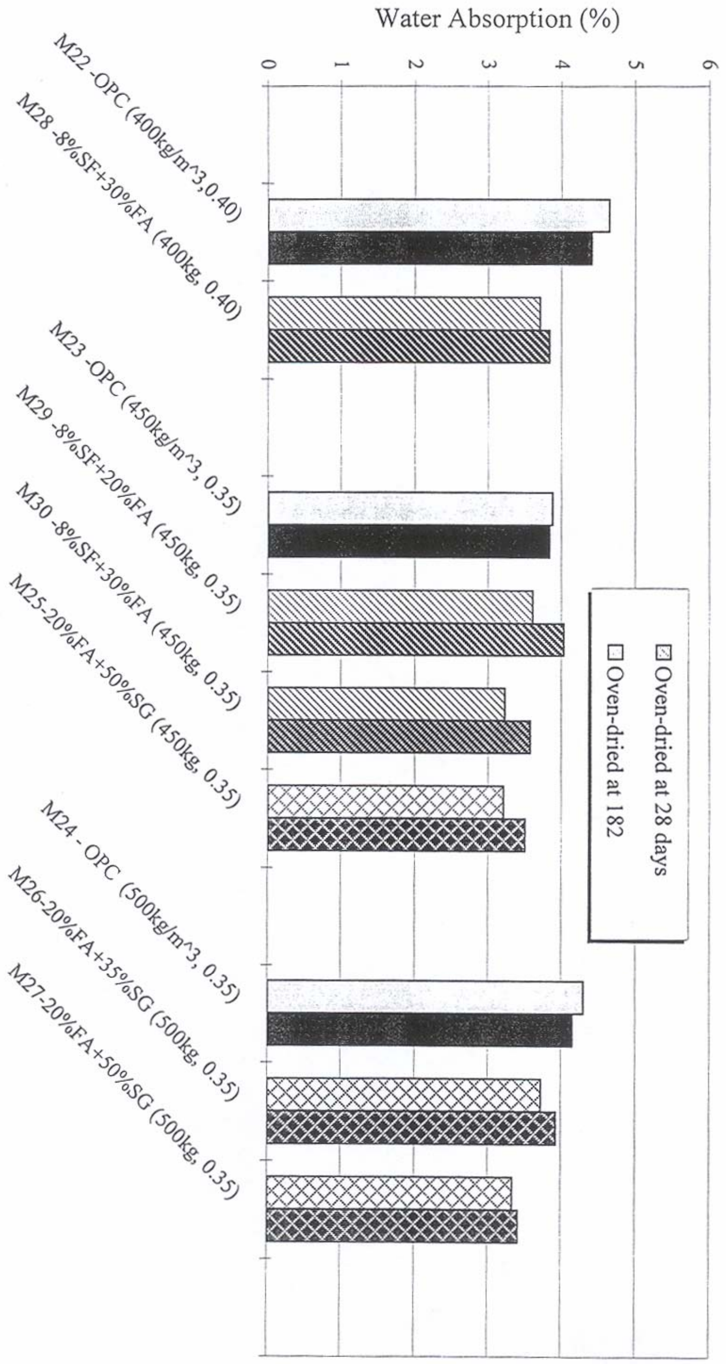


Fig 3.7-2 Water Absorption Results after Oven-Dry at Age 28 and 182 Days

Table 3.7-2. Water Absorption after Oven-Dry at 28 and 182 Days

Mix No.	Binder Type	Binder (kg/m³)	w/b Ratio	(I) Sample Oven-dried at 28 days		(II) Sample Oven-dried at 182 days		Ratio of Results I / II
				Water Absorption (%)	Ratio to PC mix	Water Absorption (%)	Ratio to PC mix	
M22	**PC**	400	0.40	**4.65**	**1**	**4.41**	**1**	**0.95**
M 28	8%SF+ 30%FA			3.71	0.80	3.84	0.87	1.04
M 23	**PC**	450	0.35	**3.88**	**1**	**3.84**	**1**	**0.99**
M25	20%FA+ 50%SG			3.21	0.83	3.51	0.91	1.09
M29	8%SF+ 20%FA			3.61	0.93	4.03	1.05	1.12
M30	8%SF+ 30%FA			3.23	0.83	3.58	0.93	1.11
M 24	**PC**	500	0.35	**4.30**	**1**	**4.15**	**1**	**0.97**
M 26	20%FA+ 35%SG			3.73	0.87	3.93	0.95	1.05
M 27	20%FA+ 50%SG			3.34	0.78	3.42	0.82	1.02

Overall, very significant differences were found between the water absorption results with air-dried specimens and that with oven-dried specimens in all the concrete mixes.

At 28 days, firstly, the water absorption percentages after the air-dry were very low in all the concretes and were in a range of 0.43% to 1.61% compared to that of 3.21% to 4.65% of the oven-dry water absorption results. The oven-dry absorption results were 3.2 to 9 times the air-dry absorption results of the nine concrete mixes. Secondly, while the air-dry water absorption values in all the ternary mixes were 1.85 to 2.33 times that of the PC controls, their oven-dry water absorption values were only 0.78 to 0.93 times that of the PC mixes.

At 182 days, when the same specimens for the 28-day tests were used again, the oven dry water absorption was 1% to 5% lower in the PC mixes but 2% to 12% higher in the ternary mixes compared to the oven-dry results at 28 days.

In the following discussions, the term "water absorption" is used for "oven-dry water absorption", while a result after air-dry preconditioning is denoted as "air-dry water absorption".

PC Concrete

At 28 Days

The difference between the water absorption results after oven-dry and air-dry was much more significant in the PC mixes than in the ternary SCM mixes. The three PC mixes had the highest ratios (5.3, 9.0 and 9.0) of the oven-dry absorption to the air-dry absorption in each group of mixes based on the same binder content and w/b ratio.

Comparing the results of M-23 and M-24 for the effect of binder content, the richer PC mix M-24 had a higher oven-dry water absorption (4.30%) than M-23 (3.88%).

The other PC mix M-22 had the lowest cement content of 400 kg/m^3 but a higher w/c ratio of 0.40 compared to 0.35 of M-23 and M-24. M-22 recorded higher water absorption than M-23 and M-24, which indicated the effect of w/c ratio was more significant than that of cement content on water absorption.

At 182 Days

When the same specimens for the 28-day tests were used again at 182 days after being stored at 23 °C in air, the oven dry water absorption in the PC mixes was slightly lower with aging. The ratio of the water absorption values at 182 days to that at 28 days was 0.95, 0.99 and 0.97 for M-22, M-23 and M-24 respectively. The ranking in performance of the three mixes was the same at 182 days as that at 28 days.

Ternary Concrete Type I: PC +8%SF +(20 or 30)%FA

At 28 Days

In this investigation, three mixes of this ternary binder all had lower oven-dry water absorption than the PC mixes. The ratio of the oven-dry absorption of a ternary mix to the PC mix was 0.80, 0.93 and 0.83 for M-28, M-29 and M-30 respectively (see Table 3.7-1).

However, the air-dry water absorption results of the three ternary mixes were all much higher than the PC mixes, although the absolute air-dry absorption values were much lower than the oven-dry absorption values. The ratio of the air-dry absorption of a ternary mix to the PC mix was 1.85, 1.88 and 2.33 for M-28, M-29 and M-30.

The much lower air-dry absorption values in all concretes can be attributed to the higher moist contents remained in the specimens even after the air-dry preconditioning from the age of 7 to 28 days. More significant increases in the absorption values were found in the PC mixes than in the ternary mixes. These differences could be resulted from the differences in the pore sizes and pore structures between the PC and SCM concretes. Further research work is needed to find and confirm the mechanisms.

The mixes M-29 and M-30 contained 20% fly ash and 30% fly ash in the ternary binder with 8% silica fume. M-30 with a higher fly ash content in the ternary binder recorded slightly lower oven-dry water absorption than M-29.

The other ternary mix M-28 had a lower cement content but a higher w/c ratio than that of M-29 and M-30. Similar to that in the PC mixes, M-28 with a higher w/c ratio recorded higher water absorption than M-29 and M-30.

The results of M-28 is not compared to that of the binary mixes M-7 and M-13 because no oven-dry water absorption results were tested in the BRC binary concrete investigation.

At 182 Days

All the three mixes of this ternary binder tested at 182 days had slightly higher oven-dry absorption values compared to that at 28 days. The ratio of the absorption value at 182 days to that at 28 days was 1.04, 1.12 and 1.11 for the three mixes.

This trend in the ternary mixes was opposite to that in the PC control mixes, in which slightly lower oven-dry absorption values were observed at 182 days. As the result, the ratio of the oven-dry absorption of a ternary mix to the PC mix increased, though not significantly, from 0.80, 0.93 and 0.83 at 28 days to 0.87, 1.05 and 0.93 at 182 days for M-28, M-29 and M-30 respectively.

Ternary Concrete Type II: PC +20%FA +(35 or 50)%Slag

At 28 Days

Similar to the results of the ternary mixes with silica fume and fly ash, three ternary mixes with slag and fly ash all had lower oven-dry water absorption, but much higher air-dry absorption, than the PC mixes. The oven-dry absorption ratio of the ternary mix to the PC mix was 0.83, 0.87 and 0.78, while the air-dry absorption ratio was 2.23, 2.27 and 1.92 for M-25, M-26 and M-27 respectively.

For the two mixes with different slag contents, the mix with higher slag content, M-27 (20%FA +50%Slag), recorded lower water absorption than M-26 (20%FA +35%Slag).

Comparing the results of M-25 and M-27 on the effect of binder content, the richer mix M27 had a slightly lower absorption than the leaner mix M-25.

At 182 Days

Similar to the results of the ternary mixes with silica fume and fly ash, all the three mixes with slag and fly ash had slightly higher oven-dry absorption values at 182 days than at 28 days. The ratio of the absorption value at 182 days to that at 28 days was 1.09, 1.05 and 1.02 for the three mixes.

This effect of specimen aging was opposite to that in the PC control mixes, in which slightly lower oven-dry absorption values were observed at 182 days. Thus, the ratios of the oven-dry absorption of the three ternary mixes to the PC mixes slightly increased from 0.83, 0.87 and 0.78 at 28 days to 0.91, 0.95 and 0.82 at 182 days.

Correlation between Water Absorption and Chloride Penetration Results

The correlation coefficients between the three water absorption test results and the results of the seven chloride penetration tests were analysed and are shown in Table 3.7-3.

Table 3.7-3. Correlation Coefficients between Water Absorption and Chloride Tests

Water Absorption Tests	ASTM C1202-28d	ASTM C1202-182d	SP(3%) 28d-91d	SP(15%) 28d-14d	SP(15%) 182d-14d	CP(15%) 28d-14d	CP(15%) 182d-14d
WA-28d-Air-Dry	-0.55	-0.68	-0.12	0.23	0.07	0.23	-0.15
WA-28d-Oven-Dry	0.93	0.83	0.90	0.55	0.85	0.69	0.87
WA-182d-Oven-Dry	0.77	0.64	0.85	0.66	0.75	0.76	0.78

Very poor correlations were found between the results of all the seven chloride tests and the water absorption results based on the air-drying precondition of the specimens.

However, the correlations between the oven-dry water absorption results at 28 or 182 days to the seven chloride tests were improved dramatically and mostly in the grade of moderate to fair.

The best correlations were found, with coefficients of 0.93 and 0.90, between the oven-dry water absorption test at 28 days and the ASTM C1202 test at 28 days and the 91-day static ponding test. The oven-dry water absorption test at 28 days also had fair correlations with the 14-days static or cyclic ponding tests at 182 days with the correlation coefficients of 0.85 and 0.87.

In general, the water absorption results based on the air-dry preconditioned specimens bore very poor correlations with the results of the seven chloride penetration tests. This indicates that the procedure of air-dry precondition used in this investigation is not appropriate for producing meaningful results in relation to the durability performance of various PC and SCM concretes. The correlations between the results of the oven-dry water absorption tests and the seven chloride tests were moderate but not strong. Since the chemical binding of chloride ions in concrete can play an important role in the resistance of concrete to chloride penetration but it may not be reflected in the water absorption test result, the use of water absorption tests as durability tests for marine concrete is questionable. However, further research work is needed in this area.

Correlation between Water Absorption Results and Compressive Strength

The correlation coefficients between the results of the water absorption tests and the 3-day, 28-day and 91-day compressive strengths were also analysed and they are presented in Table 3.7-4.

Table 3.7-4. Correlation Coefficients between Water Absorption and Strengths

Water Absorption Tests	3-Day Strength	28-Day Strength	91-Day Strength
WA-28d-Air-Dry	-0.78	-0.64	-0.33
WA-28d-Oven-Dry	0.65	0.13	-0.12
WA-182d-Oven-Dry	0.62	0.22	-0.05

It is shown in Table 3.7-4 that the correlations of the water-absorption results to the compressive strengths at 3, 28 and 91 days were generally quite poor. The positive correlation coefficients actually indicated the trend of higher strength in relation to higher water absorption, which is opposite to what would be normally expected. Therefore, the poor correlations between the compressive strengths to both chloride tests and water absorption tests confirmed that compressive strength is not a appropriate indicator for concrete durability performance in marine environment.

3.8 CARBONATION

In this test program, the carbonation test carried out was an accelerated test with high concentration of carbon dioxide, approximately 8% CO_2. The carbonation depth of specimens was measured for eight of the nine concrete mixes after 28 and 56 days exposure in the test chamber. The 751751150 mm prism specimens were moist cured in moulds for one day, followed by lime-water curing to 7 days, then air-cured at 23 °C until age of 28 days to be put in the test chamber.

Table 3.8-1 and Fig 3.8-1 present the results of the carbonation depth of the eight concrete mixes after 28 and 56 days exposure test.

In general, the PC concretes in this investigation had very low carbonation depth, from 0.5 mm to 1.7 mm, over the 28 or 56 days exposure in the accelerated tests. On the other hand, the carbonation depths of all the ternary SCM concretes were much higher than that of the PC concrete in the tests. The extension of the exposure duration from 28 to 56 days also caused significant increase in the carbonation depth of the ternary concrete specimens.

PC Concrete

Since the carbonation depths in the three PC concretes were in such a low level between 0.5 mm to 1.7 mm, the effects of cement content and the exposure time from 28 to 56 days on the test results could be identified. The only visible difference between the results of the PC mixes was that M-22 with a higher w/c ratio and lower cement content had a higher carbonation depth than M-23 and M-24.

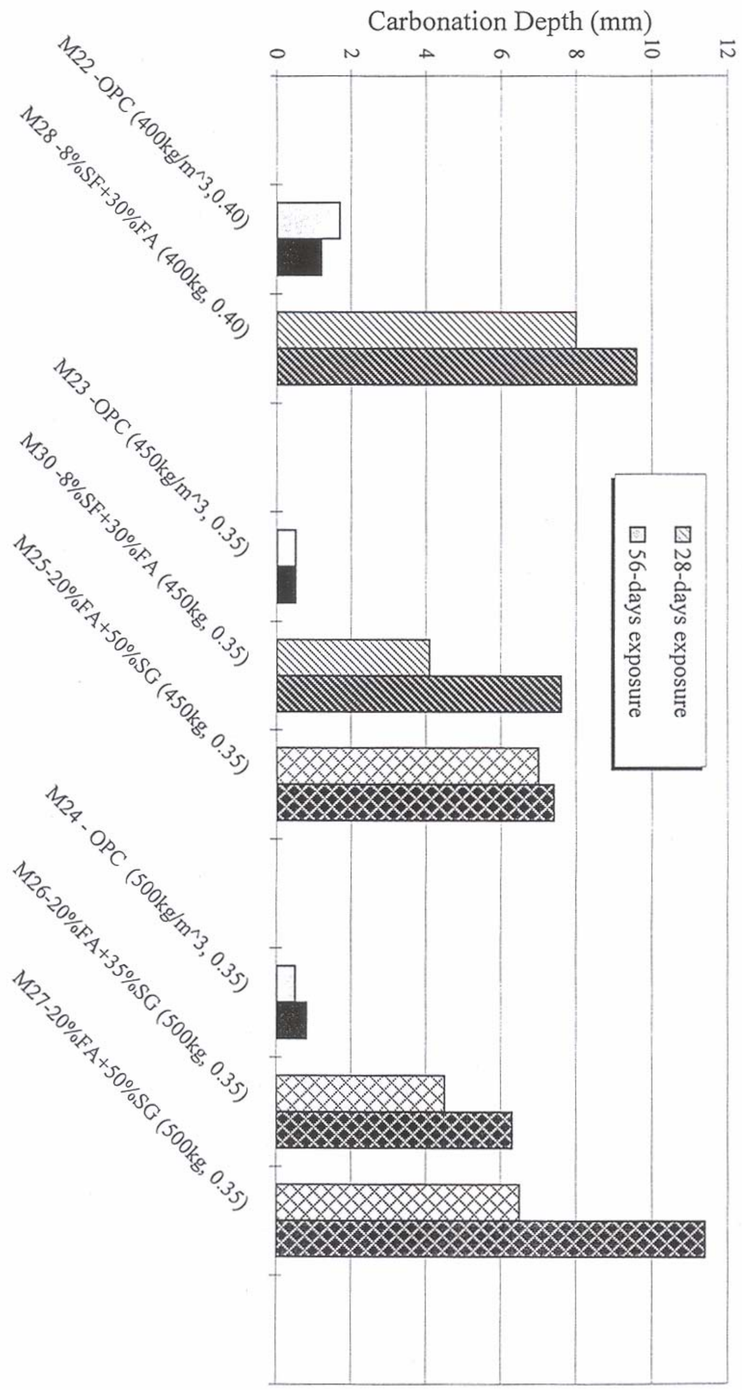


Fig 3.8-1 Results of Accelerated Carbonation Test at Age 28 Days

Table 3.8-1. Comparison of Carbonation Depth after 28 and 56 Days Testing

Mix No.	Binder Type	Binder (kg/m^3)	w/b Ratio	(I) Over 28 days		(II) Over 56 days		Ratio of Results II / I
				Carbonated Depth (mm)	Ratio to PC mix	Carbonated Depth (mm)	Ratio to PC mix	
M22	**PC**	400	0.40	**1.7**	**1**	**1.6**	**1**	**0.94**
M 28	8%SF+ 30%FA			8.0	4.7	9.6	6.0	1.20
M 23	**PC**	450	0.35	**0.5**	**1**	**0.5**	**1**	**1.0**
M25	20%FA+ 50%SG			7.0	14.0	7.4	14.8	1.06
M29	8%SF+ 20%FA			--------	--------	--------	--------	--------
M30	8%SF+ 30%FA			4.1	8.2	7.6	15.2	1.85
M 24	**PC**	500	0.35	**0.5**	**1**	**0.8**	**1**	**1.60**
M 26	20%FA+ 35%SG			4.5	9.0	6.3	7.9	1.40
M 27	20%FA+ 50%SG			6.5	13.0	11.4	14.3	1.75

Ternary Concrete Type I: PC +8%SF + 30%FA

Two ternary mixes of this binder type were tested for carbonation depth in this investigation. They both had much higher carbonation depths than the PC control mixes over 28 days exposure, 8.0 and 4.1 mm compared to 1.7 and 0.5 mm respectively. After 56 days exposure, the carbonation depths of the two ternary mixes increased to 9.6 and 7.6 mm, while virtually no increase in carbonation depth of the PC mixes.

Between the two ternary mixes, M-28 with a higher w/c ratio (0.40) and lower cement content (400 kg/m^3) had a higher carbonation depth than M-30 (450 kg/m^3 and w/c of 0.35).

The results of mix M-28 (8%SF +30%FA) were compared to that of two binary mixes, M-7 and M-13, based on the same binder content (400 kg/m^3) and w/b ratio (0.40). M-7 contained 8%SF while M-13 had 30% FA in the binary binder. Table 3.8-2 presents the test results of these three mixes and the PC control mix.

The carbonation depth in the 8% silica fume binary mix (M-7) was almost as low as the PC mix and also did not increase with the extension of exposure time from 28 to 56 days. On the other hand, carbonation rate in the 30% fly ash mix (M-13) was much higher than the PC mix and further increased significantly with the increase of the exposure time. The ternary mix (M-28) containing 8%SF+30%FA had even higher carbonation depth than the 30% fly ash mix after both 28 and 56 days exposure tests.

Table 3.8-2. Comparison of Results of Binary and Ternary Mixes

Mix No.	Binder Type	Binder (kg/m^3)	w/b Ratio	(I) Over 28 days		(II) Over 56 days		Ratio of Results II / I
				Carbonated Depth (mm)	Ratio to PC mix	Carbonated Depth (mm)	Ratio to PC mix	
M 22	**PC**	400	0.40	**1.7**	**1**	**1.6**	**1**	**0.94**
M-7	8%SF			1.8	1.06	1.8	1.13	1
M-13	30%FA			4.9	2.88	8.8	5.50	1.80
M28	8%SF+ 30%FA			8.0	4.7	9.6	6.0	1.20

Ternary Concrete Type II: PC +20%FA +(35 or 50)%Slag

In the BRC binary concrete investigation, both fly ash and slag binary mixes were found to have higher carbonation rates than the PC mixes.

In this investigation, the three ternary mixes with both slag and fly ash all had much higher carbonation rates than the PC controls and their carbonation depths increased with the extension of exposure time.

For the two mixes with different slag contents, the mix with higher slag content, M-27 (20%FA+50%Slag), recorded a higher carbonation depth than M-26 (20%FA +35%Slag). This result was similar to that in the binary concrete tests, in which the increase of slag content from 35% to 50% in the binary binder resulted in increase of the carbonation rate.

Comparing the results of M-25 and M-27 on the effect of binder content, the richer mix M27 had a slightly lower carbonation after 28 days but significantly higher carbonation depth after 56 days exposure than the leaner mix M-25.

Further Discussion

While other carbonation test results of ternary SCM concretes were very few in the literature, the test results in the BRC binary concrete investigation were generally consistent with that from other research work. In general, the silica fume replacing the PC had little effect on carbonation; the equal-mass replacement of PC with fly ash or slag resulted in a significant increase in carbonation rate.

In this investigation, the ternary concretes containing SF+FA or Slag+FA were found to have even higher carbonation rates than that of binary concretes. This may be due to the higher total percentage of SCMs in the ternary binder than that in the binary binder.

It should be emphasized that the carbonation test results of this research were based on the equal-mass replacement of the PC with SCMs. In most practical applications of fly ash or slag in concrete, especially in large proportions, the concrete mix proportions would be adjusted, normally by increasing binder content and reducing the w/b ratio.

With such modifications, the fly ash or slag concrete mixes should have a lower carbonation rate than that found in this research.

There are also some questions on the accelerated test results, which may be influenced significantly by the test age of SCM concrete, the precondition of the specimens and the carbon dioxide concentration in the tests. For example, since hydration reactions in fly ash and slag concrete takes much longer than that in PC concrete, the benefits in their microstructure improvements at later ages may not be counted in the early age accelerated test. The specimens in this investigation were air-dried before the accelerated carbonation tests similar to that for the air-dry water absorption tests. It was found, however, the water absorption results based on air-dried or oven-dried specimens were very different. Whether similar effects could be found in carbonation test results with the specimen precondition procedures needs further investigations.

More work needs to be done to develop the appropriate carbonation test procedures for SCM concretes and to correlate accelerated test results with the long-term performance of concrete containing SCMs.

3.9 SULPHATE RESISTANCE

This investigation commenced before the release of the Australian standard on sulphate resistance test (AS 2350.14-96) and therefore was carried out based on ASTM C1012. In this investigation, eight of the nine concrete mixes were tested for sulphate resistance based on the ASTM C1012 method. The length change of the specimens was measured up to 12 months after immersion in 5% sodium sulphate solution.

A modification was made to the ASTM C1012 initial curing procedure. The ASTM C1012 requires the prism specimens to be initially cured in warm water (35 °C) for 24 hours immediately after being moulded and sealed. After the initial curing and, if needed, the extended water curing at 23 °C, the specimens are placed in a sulphate solution when a strength of 20 MPa is achieved with cube specimens. These procedures were modified in this investigation due to the difficulties associated with the watertight sealing of the moulds and, also with the time needed to achieve the cube strength (20 MPa) for concretes of various w/b ratios. Some of the mixes with low w/b ratio can achieve the cube strength of 20 MPa earlier than 24 hours under 35 °C water curing. It was then decided that, in this investigation, all the samples would be moist-cured in moulds for 24 hours at 23 °C, then lime-water cured, before they would be placed in the sulphate solution until the cube strength of 20 MPa was achieved.

Fig 3.9-1 to Fig 3.9-2 show the overall test results in the forms of curves and bar charts of the expansion of specimens in 5% sodium sulphate solution up to 12 months. Table 3.9-1 gives the percentage values of specimen expansion of the eight concrete mixes and Table 3.9-2 presents the ratios of length change in specimens of the ternary mixes to that of the PC mixes.

Fig 3.9-1 Length Change of Specimens
(Sulphate Resistance Test, ASTM-C1012)

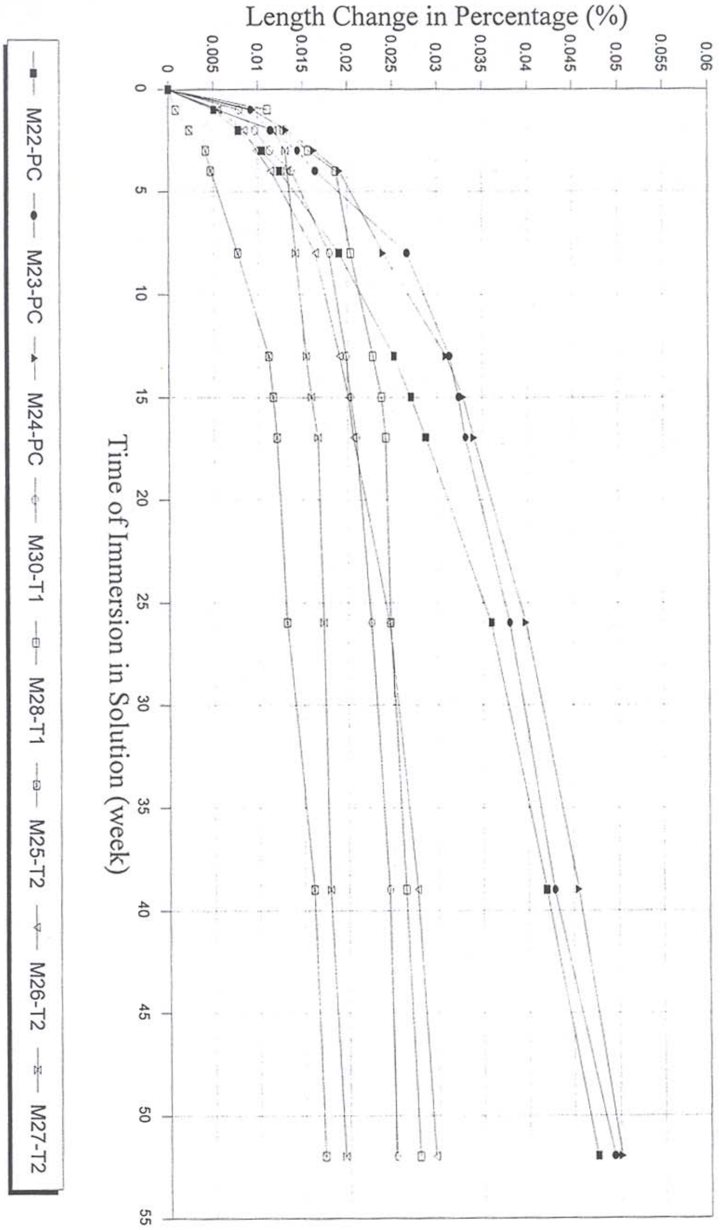


Fig 3.9-2 Results of ASTM C1012 Sulphate Resistance Test

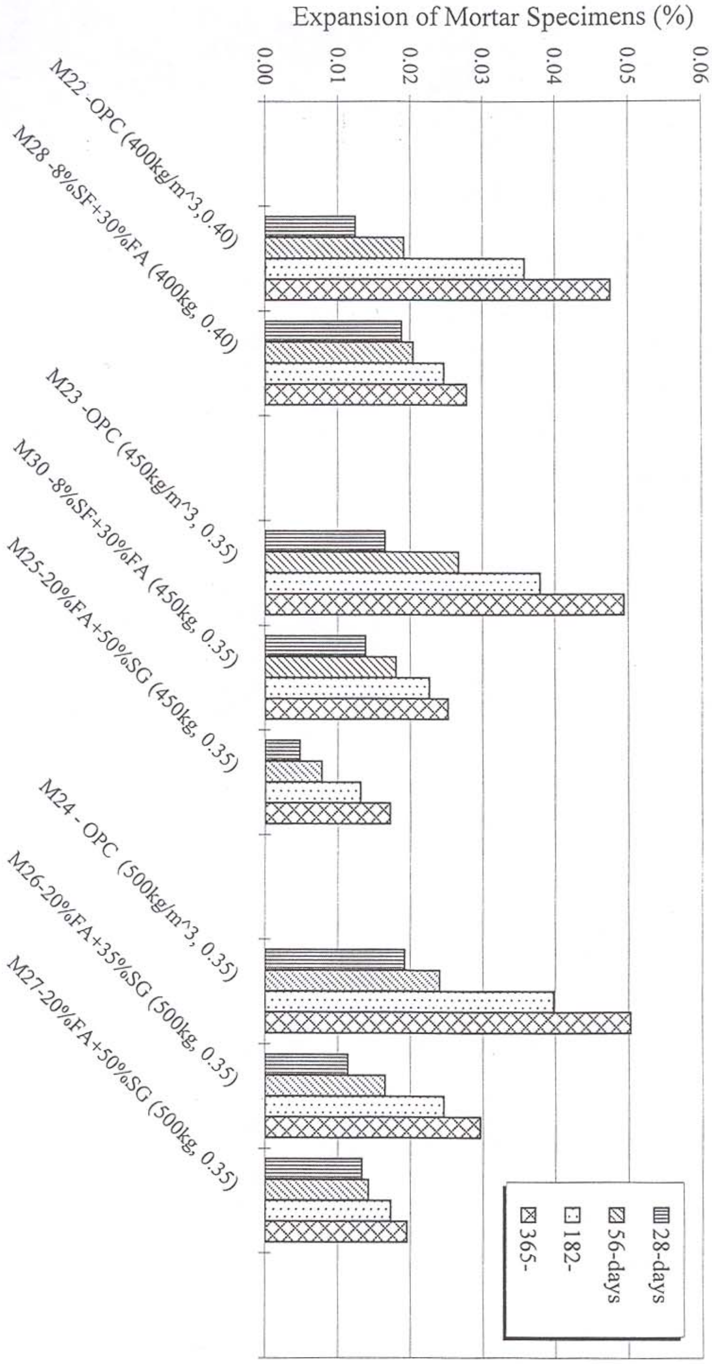


Table 3.9-1 Length Change of Specimens in ASTM C1012 Sulphate Resistance Test

Mix No.	Binder Type	Binder (kg/m^3)	w/b Ratio	Length Change of Specimens over Immersion Time (%)					
				Initial	4 weeks	8 weeks	15 weeks	6 months	12 months
M22	**PC**	400	0.40	**0**	**0.012**	**0.019**	**0.027**	**0.036**	**0.048**
M 28	8%SF+ 30%FA			0	0.019	0.020	0.024	0.025	0.028
M 23	**PC**	450	0.35	**0**	**0.017**	**0.027**	**0.032**	**0.038**	**0.049**
M25	20%FA+ 50%SG			0	0.005	0.008	0.012	0.013	0.017
M30	8%SF+ 30%FA			0	0.014	0.018	0.020	0.023	0.025
M 24	**PC**	500	0.35	**0**	**0.019**	**0.024**	**0.033**	**0.040**	**0.050**
M 26	20%FA+ 35%SG			0	0.011	0.017	0.020	0.025	0.030
M 27	20%FA+ 50%SG			0	0.013	0.014	0.016	0.017	0.020

Table 3.9-2 Ratio of Length Change in Ternary Mixes to that in PC Mix

Mix No.	Binder Type	Binder (kg/m^3)	w/b Ratio	Ratio of Specimen Length Change of SCM mixes to PC mix					
				Initial	4 weeks	8 weeks	15 weeks	6 months	12 months
M22	**PC**	400	0.40	--------	**1**	**1**	**1**	**1**	**1**
M 28	8%SF+ 30%FA			--------	1.52	1.07	0.88	0.69	0.58
M 23	**PC**	450	0.35	--------	**1**	**1**	**1**	**1**	**1**
M25	20%FA+ 50%SG			--------	0.29	0.29	0.36	0.35	0.35
M29	8%SF+ 20%FA			--------	--------	--------	--------	--------	--------
M30	8%SF+ 30%FA			--------	0.84	0.67	0.63	0.60	0.51
M 24	**PC**	500	0.35	--------	**1**	**1**	**1**	**1**	**1**
M 26	20%FA+ 35%SG			--------	0.59	0.69	0.61	0.62	0.59
M 27	20%FA+ 50%SG			--------	0.69	0.59	0.48	0.44	0.39

Overall, superior performance of all the ternary concretes to the PC controls were observed after the first thirteen weeks of immersion in the sulphate solution. As shown in Fig 3.9-1, the expansion behaviour of the PC and ternary SCM concrete specimens diverged clearly after the first thirteen weeks immersion. Afterwards, the rates of expansion in all the ternary concretes dropped to significantly low levels while that in the PC concretes remained to be relatively high. Because of this, the differences in expansion behaviour between the PC and ternary mixes became greater with the increase of the immersion time. This trend was observed continuing up to 12 months and could last for much longer if the tests were to continue.

There is no criterion specified in the ASTM C1012 as to what percentage of expansion best represent the failure of a specimen or a mix. However, the more widely accepted maximum expansion limits for moderate and high sulphate resisting cements are those proposed by Mother (Mather, 1982) and supported by Patzias's experimental data (Patzias, 1987). The proposed acceptance limits are 0.1 percent for moderate sulphate resistance and, 0.05 percent for high sulphate resistance after 180 days of exposure in ASTM C1012 test.

Based on this criterion, the sulphate resistance was very good for the PC mixes and was excellent for the ternary mixes. After six month (182 days) immersion in the sulphate solution, the three PC concretes recorded expansions in the range of 0.036 to 0.047 percent, while the expansions in the five ternary concretes were only from 0.0131 to 0.0247 percent.

PC Concrete

Having had higher rates of expansion than the ternary mixes, the three PC mixes can still be judged to have high sulphate resistance based on the criterion of less than 0.05 percent expansion after 180 days immersion in the test solution. The good performance of the PC mixes can be due to both of the low C_3A content of the cement and the relatively higher cement contents and lower w/c ratios of the concrete mixes. The type GP cement used in this investigation has a low C_3A content of about 5.8 percent.

The expansion rates of the specimens of the three PC mixes did not vary significantly in the tests. It was found, however, M-22 with the w/c of 0.40 and cement content of 400 kg/m^3 had a lower expansion than that of M-23 and M-24, which had the lower w/c ratio of 0.35 but higher cement contents of 450 and 500 kg/m^3 respectively.

Ternary Concrete Type I: PC +8%SF +30%FA

Two ternary mixes of this binder type both recorded significantly lower expansions than the PC mixes in the test. The ratios of the expansions in M-28 and M-30 and in the PC mixes were 0.69 and 0.60 after six months and were 0.58 and 0.51 after twelve months of immersion.

Between the two ternary mixes, M-28 with a higher w/c ratio (0.40) and lower cement content (400 kg/m^3) had a slightly higher expansion than M-30 (450 kg/m^3, w/c of 0.35).

The results of mix M-28 were comparable to that of two binary mixes, M-7 and M-13, based on the same binder content (400 kg/m^3) and w/b ratio (0.40). M-7 contained 8%SF while M-13 had 30% FA in the binary binder. Table 3.9-2 presents the test results of these three mixes and the PC control mix.

Table 3.9-3. Comparison of Results of Binary and Ternary Mixes

Mix No.	Binder Type	Binder (kg/m^3)	w/b Ratio	Ratio of Specimen Length Change of SCM mixes to PC mix					
				Initial	4 weeks	8 weeks	15 weeks	6 months	12 months
M 22	**PC**	400	0.40	**--------**	**1**	**1**	**1**	**1**	**1**
M-7	8%SF			--------	0.92	0.90	0.82	0.58	0.54
M-13	30%FA			--------	0.83	1.0	0.85	0.69	0.56
M28	8%SF+ 30%FA			--------	1.52	1.07	0.88	0.69	0.58

Generally to say, the two binary mixes had very similar performance in the test. The ternary mix M-28 also had a similar performance to the two binary mixes, except for the higher expansion rates at the early immersion period up to eight weeks.

Ternary Concrete Type II: PC +20%FA +(35 or 50)%Slag

In the BRC binary concrete investigation, both fly ash and slag binary mixes were found to have much lower expansion rates than the PC mixes.

In this investigation, the three ternary mixes with both slag and fly ash in the binder also recorded much lower expansion rates than the PC controls. The results were not directly comparable to that of the binary mixes due to the differences in the binder contents and w/b ratios.

For the two mixes with different slag contents, the mix with higher slag content, M-27 (20%FA+50%Slag), recorded a further lower expansion rate than M-26 (20%FA +35%Slag). This result was similar to that in the binary concrete tests, in which the increase of slag content from 35% to 50% in the binary binder further reduced the expansion of specimens.

Comparing the results of M-25 and M-27 on the effect of binder content, the richer mix M27 had a higher expansion rate than the leaner mix M-25 especially during the early immersion period.

4. SUMMARY AND CONCLUSIONS

A total of nine concrete mixes, consisting of six mixes of two ternary binder types and three PC control mixes, were investigated. These concrete mixes were divided into three groups based on the binder content, water to binder ratio and a PC control mix for each group.

The three mixes of Type-I ternary binder all contained 8% silica fume and 20% or 30% fly ash in the binder. Another three ternary mixes of Type-II all had 20% fly ash plus 35% or 50% of slag in the binder. The incorporation of two SCMs in a ternary binder was based on the equal-mass replacement of PC by the SCMs. Therefore, the comparison of the test results between a ternary concrete and its PC control concrete was based on the same binder content and water to binder ratio.

Only one of the Type-I ternary mix (M-28) was directly comparable to some binary mixes in the BRC binary concrete investigation on the basis of the same binder content and w/b ratio. The other ternary mixes had either higher binder content or lower w/b ratio than the binary SCM mixes investigated.

4.1 WORKABILITY

All the nine concrete mixes were investigated for their water demand and slump loss percentage over 30 minutes.

4.1.1 Water Demand

The water demand of a concrete mix was judged by the amount of water reducer and superplasticiser that was required to achieve the target 80 ±20 mm initial slump.

It was found in the BRC binary concrete investigation, that silica fume and slag concrete had a higher water demand, while fly ash concrete had a lower demand, compared to the PC control concrete.

The ternary concrete containing both silica fume and fly ash was found to a have higher water demand than the PC concrete, but lower than that of the binary silica fume concrete.

In the ternary concrete containing both slag and fly ash, two of the three mixes had a higher water demand than the PC concrete. The ternary concrete, however, generally had lower water demand than the binary slag concrete.

4.1.2 Slump Loss Over 30 Minutes

As in the binary concrete investigation it was found, that in the PC mixes a significant relationship existed between the slump loss and the free water content in the mix: the lower the water content, the higher the slump loss over 30 minutes after mixing.

A similar trend was also found in either the binary or the ternary concrete mixes. However, the effect of water content on the slump loss was much less significant in SCM concrete than that in PC concrete due to the additional effects of the SCMs on the slump loss.

The ternary concrete with both silica fume and fly ash had a similar or lower slump loss than the PC concrete. The slump loss of the ternary concrete was of the same order as that of the silica fume and fly ash binary concretes.

In the ternary concrete containing both slag and fly ash, the slump loss was higher than in the PC concrete. Increased slag content in the ternary binder also resulted in an increase in the slump loss.

It should be pointed out, that in this laboratory investigation the concrete remained untouched after being mixed and discharged. The slump loss was measured with the non agitated concrete. Therefore, only the relative performances between the concrete mixes in this program were compared, since the values of slump loss can be quite different to that in readymix concretes, which are under continuous agitation.

4.2 SETTING TIME

Seven of the nine concrete mixes were tested for initial and final setting time according to the AS C1202.

For the two PC concrete mixes with the same w/b ratio but different cement contents of 450 and 500 kg/m^3, the initial and final setting of the richer mix was two hours earlier than that of the leaner mix.

It was found in the binary concrete investigation that all the three binary SCM concretes had a delayed time of setting compared to the PC control concrete. The delay in setting was more pronounced in the slag or fly ash concretes than in the silica fume concrete.

In this investigation, the ternary concretes had even longer setting times than the binary SCM concretes. The delay in the initial setting compared to the PC mixes was 40 to 180 minutes for the ternary concrete with both silica fume and fly ash, and 260 to 355 minutes for the ternary concrete containing slag and fly ash.

The ternary concrete containing both slag and fly ash due to its extended setting time as well as its low heat generation would be beneficial in the continuous placing of a large volume of concrete .

4.3 BLEEDING

Seven of the nine concrete mixes were tested for bleeding behaviour according to AS C1202.

For the two PC concrete mixes with the same w/b ratio but cement contents of 450 and 500 kg/m^3, the ratio of bleed of the richer mix was slightly higher than that of the leaner mix.

It was found in the binary concrete investigation, that the silica fume concrete had a lower bleed, while the fly ash and slag concrete had a higher bleed when compared to the PC concrete.

In this investigation, the ternary concrete with both SF and FA had much lower bleed than the binary fly ash concrete. One such ternary mix recorded a higher bleed than the PC control, while the other two mixes had lower bleeds than the PC concrete.

The two ternary mixes containing slag and fly ash both had a higher bleed than the PC control concrete, 3.8% to 4.1% compared to 1.49%. The ternary mix with a higher slag content had the higher bleed of 4.1%.

In the binary and ternary concrete investigations it was found that the relative fineness of the SCMs to the PC was not the sole control parameter on the bleed behaviour of SCM concrete. A higher bleed ratio was observed in the slag cement concrete although the blended slag cements were ground finer than the PC. Further research is needed to fully explain such phenomena. At this stage it is assumed that besides the fineness of PC and SCMs, the grain particle shape and the chemical reactivity of PC and SCMs are also important parameters affecting bleeding in concrete. The higher bleed in fly ash and slag concrete may be partly due to the dormant and slow chemical reactions of fly ash and slag.

4.4 TEMPERATURE DEVELOPMENT IN CONCRETE

The seven concrete mixes investigated for temperature development were the same as those tested for setting time and bleeding. The temperature development history was measured at the centre of a 300mm concrete cube which had been completely encapsulated in polystyrene foam. The maximum temperature rise was defined as the difference between the maximum temperature in the concrete block and the ambient temperature when the block was cast.

The maximum temperature rise in the three PC control mixes was 32.3 to 36.7°C compared to that of 15 to 24.4 °C in the ternary mixes. For the two PC concrete mixes with different cement contents of 450 and 500 kg/m^3, a slightly higher maximum temperature rise of 36.7°C was recorded in the richer mix compared to that of 35.9°C in the leaner mix.

In the binary concrete investigation, the replacement of PC with either slag or fly ash in the binder reduced the maximum temperature rise significantly, while 8% silica fume in the binder had little effect on the temperature.

In this investigation the maximum temperature rise in the two ternary mixes with 8% silica fume and 30% fly ash was reduced by 41% and 39% compared to that of the PC mixes. The fly ash was found to be the key ingredient in reducing temperature rise in the ternary mixes, while the silica fume had little effects on temperature rise.

In the two ternary mixes both containing 20% fly ash but 35% and 50% slag, the maximum temperature rise was reduced by 33% and 59% compared to that in the PC mixes. Similarly to that in the binary concrete, an increase in the slag content resulted in a further lowering of the temperature in the concrete.

Not only the maximum temperature, but also the slope of the temperature rise and drop was reduced significantly in the ternary mixes. Both effects reduce the thermal gradient and thermal stresses, thereby reducing the potential of thermal cracking in concrete.

4.5 COMPRESSIVE STRENGTH

The compressive strength of each of the nine concrete mixes was tested at the age of 3, 28 and 91 days according to AS 1012.

Overall, the compressive strength of the nine mixes was in the range of 49.6 to 68.9 MPa at 28 days. In general, the ternary mixes in this investigation had a lower strength than the PC mixes at all ages, except for two that at 91 days had developed a higher strength than the PC mixes.

For the two PC concrete mixes with a w/b ratio of 0.35 but cement content of 450 and 500 kg/m^3, the richer mix had a slightly lower strength at 28 and 91 days but a slightly higher strength at 3 days. The third PC mix with a lower cement content (400 kg/m^3) and a higher w/b ratio (0.40) had a much lower strength at all ages. Therefore w/b ratio had a much more significant effect on concrete strength than the cement content.

Except for one of the ternary mixes at 91 days, the three ternary mixes with both silica fume and fly ash, generally, had a lower strength than the PC mixes at 3, 28 and 91 days. The strength ratios of the three ternary mixes to the PC mixes were in the range of 0.63 to 0.76 at 3 days, 0.92 to 0.94 at 28 days and 0.93 to 1.06 at 91 days.

The mix (M-28) containing 8% silica fume and 30% fly ash was comparable to the binary concrete mixes with 8% silica fume (M-7), and 30% fly ash (M-13) based on the same binder content and w/b ratio. The results indicated that M-28 even had a slightly lower strength at all ages than the binary mix M-13 which only contained 30% fly ash. Some results in the literature also appear to support the finding, that further replacement of PC with silica fume in a binder containing 30% or more fly ash had little beneficial effects on the concrete strength. Further investigations are needed on the strength of ternary concrete containing both silica fume and fly ash.

Except for one mix at 91 days, the three ternary mixes with both slag and fly ash also had a lower strength than the PC mixes at 3, 28 and 91 days. The strength ratios of three such ternary mixes to the PC mixes were in the range of 0.43 to 0.59 at 3 days, 0.73 to 0.99 at 28 days and of 0.80 to 1.15 at 91 days.

For the ternary mixes containing 20% fly ash the strength was reduced, with an increase of the slag content from 35% to 50%, while an optimal strength gain was found for the binary mix with 50% slag content. The richer ternary mix of this type was also found to have a higher strength than the leaner mix. This was the opposite of` that found in the PC mixes. Further research work is needed in these areas.

4.6 CHLORIDE PENETRATION

All the nine concrete mixes were tested with the seven chloride penetration tests based on the following four test methods:

- rapid chloride permeability test (ASTM C1202 or AASHTO-T277) at 28 and 182 days
- 3% NaCl static ponding test at 28 days over 91 days
- 15% NaCl static ponding test at 28 and 182 days over 14 days
- 15% NaCl cyclic ponding test at 28 and 182 days over 14 days

The specimens in the ASTM C1202 tests were continuously cured in lime-water before testing. The specimens in the other six tests were all moist-cured in moulds for 1 day, followed by lime-water curing to 7 days, then air-cured at 23 °C until the age of testing.

4.6.1 ASTM C1202 TEST AT AGE 28 AND 182 DAYS

Overall, the test results of all the nine mixes were in the range of 1127 to 3780 coulombs at the concrete age of 28 days, and of 236 to 2437 coulombs at 182 days. Based on the criteria given in the ASTM C1202, the test results can be interpreted to show that the chloride ion penetrability in the six ternary mixes was "very low" while in the three PC mixes it was at a ‘moderate’ level.

The three PC mixes recorded electrical charges of 3047 to 3780 coulombs in the tests at 28 days. For the two PC concrete mixes with the same w/b ratio, the richer mix had a significantly higher coulomb value. This significant effect of the cement content on the coulomb value was also identified in the binary concrete investigation. This effect might be due to the higher calcium hydroxide content in the richer mix, rather than to higher chloride penetrability. The coulomb values of the three PC mixes at 182 days were reduced to 0.62 to 0.80 times that at 28 days. While the difference in coulomb values at 182 days became smaller, the performance ranking of the three mixes was opposite to that at 28 days.

The three ternary mixes with both silica fume and fly ash had much lower charges than the PC mixes at 28 days, and extremely low values at 182 days. The ratios of the coulomb values of the three ternary mixes to the PC controls were from 0.37 to0.44 at 28 days, but 0.10 to 0.14 at 182 days. It was found in the binary concrete investigation, that the reduction of coulomb value with age was more pronounced in the fly ash mixes than in the silica fume mixes. In the ternary mixes with 8% silica fume and 30% fly ash in the binder, the age effect was between that of the binary mixes containing 8% silica fume and 30% fly ash respectively.

The three ternary mixes with both slag and fly ash also had much lower charges than the PC mixes at 28 days and extremely low values at 182 days. The ratios of the coulomb values of the three ternary mixes to the PC controls were from 0.32 to0.47 at 28 days, but 0.15 to 0.17 at 182 days.

4.6.2 STATIC PONDING TEST IN 3% NaCl SOLUTION OVER 91 DAYS

Overall, the chloride penetration depths in the nine concrete mixes over 91 days ponding, were in the range of 7.5 to 12.3 mm. All the ternary concrete mixes had less chloride penetration than the PC control mixes. However, the differences in chloride penetration between the ternary and PC concretes were much less pronounced than that in the coulomb values of the ASTM C1202 test.

The three PC mixes recorded the highest range of chloride penetration depth from 9.4 to 12.3 mm in this test. Unlike that in the ASTM C1202 test the effect of cement content was not significant on the chloride penetration in the two PC mixes (9.4 and 9.9 mm) with the same w/b ratio (0.35) but different cement contents (450 and 500 kg/m^3). On the other hand, the third PC mix with a higher w/b ratio (0.40) but a lower cement content (400 kg/m^3) had a much higher chloride penetration (12.3 mm). The coulomb value of this mix (w/b of 0.40) was between those of the two mixes with w/b of 0.35. The chloride penetration in the 91 day ponding test was more sensitive to w/b ratio rather than the cement content, while the coulomb values in the ASTM C1202 test had similar sensitivity to both of these parameters.

The three ternary mixes with both silica fume and fly ash all had a lower chloride penetration than the PC mixes. However, the ratios of the test results of the three ternary mixes to the PC mixes were from 0.79 to 0.93. These were much higher than those of the coulomb values from 0.37 to0.44 at 28 days and 0.10 to 0.14 at 182 days in the ASTM C1202 tests.

The three ternary mixes with both slag and fly ash also had a lower chloride penetration than the PC mixes. The ratios of the test results of the ternary mixes to the PC mixes were from 0.76 to 0.83. Similarly to the observations in the binary concrete investigation, the ternary mix with a higher slag content (50% versus 35%) recorded a lower chloride penetration depth. The effect of binder content on the chloride penetration was not significant in the two ternary mixes of this type.

4.6.3 STATIC PONDING (15% NaCl) OVER 14 DAYS AT 28 AND 182 DAYS

Overall, the chloride penetration depths, in the nine concrete mixes over 14-days ponding in 15% NaCl solution, were in the range of 5.2 to 9.6 mm when tested at 28 days and 7.4 to 15.2 mm when tested at 182 days. The aging of specimens in air at 23 °C between 28 to 182 days resulted in a higher chloride penetrability in both PC and SCM concretes. This increase in the chloride penetration due to the aging of specimens in air was the highest in the PC concrete, slightly lower in the ternary concrete with slag and fly ash, and the lowest in the ternary concrete with silica fume and fly ash.

Only in the tests at 182 days did all the ternary concrete mixes have less chloride penetration than the PC control mixes. At 28 days the two ternary mixes containing both silica fume and fly ash had a higher chloride penetration than the PC control. In the binary concrete investigation, fly ash binary concrete was also found to have higher chloride penetration than the PC control in the 14-days ponding test at 28 days.

The three PC mixes in the 14-days test at 28 days had lower chloride penetration depths than that in the 91day (3% NaCl) test. However, when tested at 182 days they had a higher chloride penetration than that in the 91 day test. The ratios of the test results at 182 days to that at 28 days were 1.58, 1.49 and 1.27 for the three PC mixes. The chloride penetration in the PC concrete was also more sensitive to w/b ratio than the cement content at both 28 and 182 days.

The three ternary mixes with both silica fume and fly ash recorded much smaller increases in chloride penetration than the PC concrete when tested at 182 days compared to that at 28 days. Therefore the chloride penetration of the three ternary mixes to the PC mixes were 0.95, 1.28 and 1.34 in the test at 28 days but reduced to 0.75, 0.78 and 0.92 at 182 days. The chloride penetration in the ternary mixes with 8% silica fume and 30% fly ash (9.1 mm) was found to be mid-way to that in the binary mixes containing 8% silica fume (5.8 mm) and 30% fly ash (12.5 mm).

The three ternary mixes with both slag and fly ash all had lower chloride penetration than the PC mixes at both 28 and 182 days. The ratios of the test results of these ternary mixes to the PC mixes were from 0.75 to 0.83 at 28 days and from 0.72 to 0.83 at 182 days. As in the binary slag concrete, the ternary mix with a higher slag content (50% versus 35%) recorded a lower chloride penetration depth. The effect of the binder content on the chloride penetration was not significant in the two ternary mixes with the same w/b ratio.

4.6.4 CYCLIC PONDING (15% NaCl) OVER 14 DAYS AT 28 AND 182 DAYS

This investigation confirmed that compared to the static ponding test, the wet-and-dry cyclic ponding procedure accelerated chloride penetration, especially when both tests were conducted at the age of 28 days.

Overall, the chloride penetration depths in the nine mixes in the cyclic test were from 7.1 to 12.0 mm (5.2 to 9.6 mm in static test) at 28 days, and from 7.4 to 18.4 mm (7.4 to 15.2 mm in static test) at 182 days. The aging of specimens in air at 23 °C between 28 to 182 days resulted in a higher chloride penetrability in both the PC and SCM concrete. This increase in chloride penetration, however, was much higher in the PC concrete than in the two types of ternary concrete.

As in the static test, all the ternary concrete mixes had lower chloride penetration than the PC control mixes at 182 days. The two ternary mixes containing both silica fume and fly ash, however, had a higher chloride penetration than the PC control mix at 28 days.

For the three PC mixes the ratios of the test results at 182 days to that at 28 days were 1.54, 1.55 and 1.20, much higher than those for the six ternary mixes from 0.88 to 1.16. Similarly to the two static ponding tests the chloride penetration in the PC concrete in the cyclic ponding test was more sensitive to w/b ratio rather than the cement content at both 28 and 182 days.

Due to aging in air, the three ternary mixes with both silica fume and fly ash recorded a much smaller increase in chloride penetration than the PC concrete. As a result, the chloride penetration of the three ternary mixes to the PC mixes were 0.91, 1.22 and 1.08 in the test at 28 days but reduced to 0.60, 0.69 and 0.72 at 182 days. At 28 days the chloride penetration in the ternary mixes with 8% silica fume and 30% fly ash was mid-way between the binary mixes containing 8% silica fume and 30% fly ash. However, at 182 days, the chloride penetration in this ternary mix (11.1 mm) was slightly lower than that in the fly ash binary mix (12.1 mm) and much lower than that in the silica fume binary mix (16.3 mm). The BRC binary concrete investigation found a much poorer performance of the silica fume binary concrete at 182 days. This was improved by the use of a ternary binder, which also contained fly ash.

Three ternary mixes with both slag and fly ash all had a lower chloride penetration than the PC mixes, at both 28 and 182 days. The ratios of the test results of these ternary mixes to the PC mixes were from 0.73 to 0.91 at 28 days, and from 0.65 to 0.76 at 182 days. Similarly to that in the binary slag concrete, the ternary mix with a higher slag content (50% versus 35%) recorded a lower chloride penetration depth. The effect of the binder content on the chloride penetration was not significant, although a slightly lower chloride penetration was observed in the richer mix.

4.6.5 COMPARISONS OF CHLORIDE TEST RESULTS AND METHODS

Performance of PC and Ternary Concretes in Seven Chloride Penetration Tests

Compared to the PC control mixes, the ternary concrete containing both fly ash and slag performed better in all the seven chloride penetration tests. However in two of the seven tests, the other ternary concrete with silica fume and fly ash, performed worse than the PC mixes. The test methods and the testing age significantly affected the performance levels of the ternary concretes when compared to the PC controls .

Overall, the seven chloride tests can be classified into two groups according to the significant differences in the relative performance levels of the ternary mixes compared to the PC mixes. One group consists of only the two ASTM C1202 tests at 28 and 182 days, while the other group consists of the other five static and cyclic ponding tests.

In the ASTM C1202 test, the two types of ternary concrete had similar performances. The ratios of the coulomb values of the ternary concretes to the PC concrete were very low (0.32 to 0.47) at 28-days and extremely low (0.10 to 0.17) at 182-days.

However, in all the five static and cyclic ponding tests the relative chloride penetration ratios of the two types of ternary concrete were much higher than that in the ASTM C1202 tests. The two types of ternary concrete also had some differences in their performances in the static and cyclic ponding tests.

The ternary concrete with slag and fly ash had better performance than the PC concrete in all the five tests: with relative chloride penetration ratios from 0.65 to 0.91. On the other hand, the ternary concrete with silica fume and fly ash only had a better performance than the PC concrete in three of the five tests: with relative chloride penetration ratios from 0.60 to 0.93. In both the static and cyclic ponding tests at 28 days over 14 days, two of the three silica fume and fly ash ternary mixes had higher chloride penetration than the PC controls.

The differences between the results of the ASTM C1202 test and the static and cyclic ponding tests were also found to be more pronounced in the ternary concrete tests than that in the binary concrete tests. The higher percentages of SCMs in the ternary binders might be the main reason for this observation.

The effect of specimen testing age on chloride penetration in the static and cyclic ponding tests was found to be the opposite to that on coulomb value in the ASTM C1202 test. Although in this program the specimen curing condition was different in the ASTM C1202 test and the ponding tests, it cannot be considered to be the sole reason for the opposite age effects. Since other research work has also shown that a reduction in coulomb value occurs with air-dry aging, further research is needed in this area.

Correlation between the Chloride Penetration Tests

The statistical analysis of the correlation coefficients indicates a significant difference between the two groups of tests: the two ASTM C1202 tests and the five static and cyclic ponding tests. In general, the correlation coefficient between two tests within the same group was much higher than that between two tests of different groups.

The results between the ASTM C1202 test at 28 and 182 days had a good correlation (coefficient of 0.96), however, their correlation with the results of the other five tests were from very poor to moderate (0.21 to 0.79). The three chloride ponding tests: two at the latter age of 182 days over 14-days and one at 28 days over 91-days correlated very well (coefficient of 0.96 to 0.97). For the tests at 28 days over 14-days, the cyclic ponding test had fair correlations with the above three tests (0.78 to 0.89), while the static ponding test had slightly weaker correlations with other tests (0.59 to 0.89).

The correlation between the ASTM C1202 tests and the chloride ponding tests were found to be poorer than that in the binary concrete investigation. This, however, corresponded well with the more pronounced differences between the results of the ASTM C1202 and the ponding tests in the ternary mixes.

Correlation of the Chloride Penetration Tests with Compressive Strength

The statistic analysis of the test results indicates a very poor or no significant correlation at all between the results of any of the seven chloride penetration tests and concrete compressive strength at 3, 28 or 91 days. The correlation between the chloride tests and the compressive strength was also much poorer than that in the binary concrete investigation. This could be partly due to the higher total SCM content and the higher binder content in the ternary concrete mixes compared to that in the binary mixes.

It can be concluded, that the compressive strength of SCM concretes does not have a significant correlation with the performance of the concretes against chloride penetration, especially when higher percentages of SCMs are used. Therefore, in marine environments it is not appropriate to use compressive strength as an indicator of concrete durability.

Further Comments on the Chloride Penetration Test Methods

In the BRC report on the binary concrete investigation (Chang et. al, 1998) the three categories of chloride penetration test methods, the ASTM C1202, the static ponding and the cyclic ponding tests, are discussed in more detail. The ASTM C1202 is considered to be attractive due to its simplicity. However, further research work is needed to provide sound scientific basis for the method and the correlation between coulomb value and real resistance to chloride penetration. Although static ponding tests are suitable and simple to carry out, they may be only suitable for concrete in submerged marine structures. Wet-and-dry cyclic ponding tests are considered to simulate more closely the mechanisms of chloride penetration into concrete used above water in coastal environments. Besides, the specimen age and the test condition, duration was found to have varying effects on the performance of the PC and the different SCM concretes. The silica fume concrete, for example, had a much better relative performance in the static ponding test than in the wet-and-dry cyclic test, especially over a longer test duration or at later ages. To provide a reasonable and a less biased assessment of PC and SCM concretes, an optimal test procedure needs to be further investigated for both the static and the cyclic ponding tests.

In this investigation of SCM concrete with ternary binders, the test results generally support the above views. Besides, the differences between the results of the ASTM C1202 test and the static and cyclic ponding tests were found to be more pronounced in the ternary mixes. The ternary concrete containing both silica fume and fly ash did not have the same sensitivity as the silica fume binary concrete to the wetting-and-drying condition. A very good correlation was found between the ponding test at 28 days over 91-days and the static or cyclic ponding test at 182 days over 14-days.

For quality control in concrete construction the development of accelerated test procedures at a relatively early age and over a short test duration is necessary. In the BRC binary concrete investigation, the cyclic ponding test at 28 days, over 28-days appeared to be an appropriate test procedure to give a reasonable assessment of the performance of PC and SCM concrete at later ages. It may, however, be possible to further reduce the test duration of the cyclic test or static ponding test based on the findings in the ternary concrete investigation.

Further accelerated and more consistent chloride ponding results were observed at later ages or over a longer duration in the wet-and-dry cyclic test. This is most likely to be associated with more uniform moisture contents in the specimens and a higher degree of concrete maturity. In general, chloride penetration into concrete can be modelled by the combination of transport mechanisms of capillary suction, chloride ion diffusion and/or permeation. The pore sizes and pore structures play the most important roles in these mechanisms. However, a certain degree of hydration or maturity of the concrete is essential, if most of the continuous capillaries are to be eliminated. It is well established that both slag and fly ash concrete take a longer time to mature than PC concrete. On the other hand, the moisture content in the pores, for a particular pore system of the concrete, is also a major parameter for these chloride transport mechanisms.

If the above assumed reasons for consistent test results are correct, it would then be possible to accelerate both processes by an appropriate oven-drying procedure to precondition the specimens before a static or cyclic ponding test. For a static ponding test this test procedure appears to have some similarities to a water absorption test but also to have some differences. It has been observed in absorption tests in other research with salt solution that the penetration front of the chlorides lags behind the water front in most cases. This can be attributed to the binding of the chloride ions by the hydration products; this phenomenon would vary in concretes with different binders. Therefore, two test results can be obtained with the "salt solution absorption test". Firstly, the absorption result measured by weight gain and secondly, the chloride penetration depth detected by spraying silver nitrite solution on the split specimen section. However, only experimental investigations can tell whether such simple and accelerated tests would provide satisfactory results for the assessment of chloride penetrability in both PC and SCM concrete. Optimal preconditioning procedures such as the drying temperature and time period, as well as the side effects of the oven-drying process on the microstructures of concrete, need to be evaluated through further research work.

4.7 WATER ABSORPTION

The three water absorption results of all the nine concrete mixes were measured under the following preconditions and ages: air-dried at 28 days, and oven-dried at 28 and 182 days. All the specimens were initially cured in lime-water for 7 days.

Performance of PC and Ternary Concretes in Seven Chloride Penetration Tests

At the age of 28 days, the water absorption results of the air-dried specimens and the oven-dried specimens were dramatically different for all the concrete mixes. Firstly, the oven-dry absorption values were 3.2 to 9 times the air-dry absorption values for the nine concrete mixes. Secondly, comparing to the PC concrete, all the ternary mixes had much higher air-dry water absorption (1.85 to 2.33 times), but had a lower oven-dry water absorption (0.78 to 0.93 times).

At 182 days, the oven-dry water absorption was 1% to 5% lower in the PC mixes, but 2% to 12% higher in the ternary mixes, when compared to the oven-dry results at 28 days.

The much lower air-dry absorption values measured at 28 days can be attributed to the higher moisture content in the specimens even after air-drying from 7 to 28 days. It has been acknowledged that moisture content in concrete is a major parameter governing water absorption results. The dramatically different performance of ternary and PC concrete, based on the air-dry or oven-dry absorption results was most likely due to variations in the moisture content of PC and SCM concretes after air-dry. While the moisture content in concrete after air-drying, can vary quite significantly due to different pore sizes and structures, oven-drying at 105 °C would create a fairly uniform moisture content in different concretes.

On the other hand, an appropriate oven-dry procedure may also accelerate concrete maturity to some extent. This procedure can have more pronounced effects on concrete containing SCMs, however, it appears to be a fair procedure for using accelerated tests to assess long-term durability performance of concrete at early ages. Further research work is needed to identify the overall impacts, either positive or negative, of an oven-dry procedure on chloride penetration test results.

Correlation between Water Absorption and Chloride Penetration or/and Strength

The air-dry water absorption results had very poor or no significant correlation at all with the results of the seven chloride penetration tests. This indicates that the air-drying procedure used in this investigation is not appropriate for producing meaningful results in relation to the durability performance of concrete.

On the other hand, the oven-dry water absorption results were found to have a much better correlation with the results of the seven chloride tests. The best correlations (coefficients of 0.93 and 0.90) were found between the oven-dry water absorption test at 28 days and the ASTM C1202 test at 28 days, and the 91-days static ponding test. The oven-dry water absorption test at 28 days also had fair correlations with the 14 day static ponding test and the cyclic ponding tests at 182 days with the correlation coefficients of 0.85 and 0.87.

However, since water absorption tests do not consider the effects of chloride diffusion and chloride binding by hydration products, the use of these tests as durability tests for marine concrete is questionable. Therefore, further research work is needed in this area as well as in developing the "salt water absorption and chloride penetration" test.

4.8 CARBONATION

Eight of the nine concrete mixes were tested for carbonation depth in an accelerated test over 28 and 56 days in a chamber containing approximately 8% CO_2 carbon dioxide.

In general, the PC concrete in this investigation had a very low carbonation depth, from 0.5 mm to 1.7 mm, over both the 28 and the 56 days accelerated test. On the other hand, the carbonation depths of all the ternary mixes were much higher than that of the PC concrete in the tests. The extension of the duration of the exposure from 28 to 56 days also caused a significant increase in the carbonation depth in the ternary concrete specimens.

In this investigation, the ternary concrete containing either SF+FA or Slag+FA was found to have even higher carbonation rates than that of the binary concretes containing one of these SCMs. This could be due to the higher total percentage of SCMs in the ternary binder than that in the binary binder.

The specimens in this carbonation test were air-dried before the accelerated carbonation tests the same way as for the air-dry water absorption test. The water absorption results were found to be very different in the air-dried and in the oven-dried specimens. The non-uniform moisture content in the specimens of the different concretes was most likely a major cause of these differing results. Similarly to that in water absorption, the moisture content of specimens would also affect the gas flow and diffusion into the concrete. Whether significantly different results would be obtained in the carbonation test with oven-dried specimens needs further investigation.

4.9 SULPHATE RESISTANCE

Eight of the nine concrete mixes were tested for sulphate resistance based on ASTM C1012 and the length change of specimens was measured up to 12 months.

Overall, the superior performance of all the ternary concretes to the PC controls became clear after the first eight to thirteen weeks of immersion in the sulphate solution. The differences in total expansion between the PC and the ternary mixes became greater with an increase of the immersion time.

There is no criterion specified in the ASTM C1012 for the failure of a specimen or a mix. However, based on the proposed limits of 0.05 percent for high sulphate resistance after 180 days of immersion (Mather, 1982, Patzias, 1987), the sulphate resistance was very good for the PC mixes, and excellent for the ternary mixes. After six month (182 days) immersion in the sulphate solution, the three PC concretes recorded expansions in the range of 0.036 to 0.047 percent, while the expansion in the five ternary concretes was from only 0.013 to 0.025 percent. The total expansion after twelve months immersion was 0.048 to 0.050 percent in the PC mixes and 0.017 to 0.030 in the ternary mixes.

For the two mixes containing 8% silica fume and 30% fly ash in the ternary binder, the relative expansion compared to the PC mixes was 0.69 and 0.60, after six-months testing. Comparing to the binary mixes with 8% SF or 30% FA, the ternary SF+FA mix was found to have a higher expansion rate in the first eight weeks, but only a slightly higher total expansion subsequently.

Two of the three ternary mixes containing both slag and fly ash (20%FA+50%SG) had the best performance within the eight mixes investigated. However, the third such mix with 35% slag content had a slightly higher expansion. As for the effect of binder content, it appears that a richer mix of this ternary binder had a higher expansion, especially, in the first three months.

5. RECOMMENDATIONS FOR FURTHER RESEARCH WORK

The test results of the research program investigating both binary and ternary SCM concrete suggest that further research is required in the following areas.

5.1 Chloride Penetration Tests for Concrete Performance Specifications

Currently there are few test methods, which are widely accepted for testing chloride penetrability in concrete containing supplementary cementitious materials (SCMs) as well as ordinary portland cement. Research work is necessary to further develop suitable test methods for the construction industry, in specification and quality control of concrete in marine environments.

The results of this research program indicate that the various test methods and exposure conditions have a significant influence on the chloride penetration test results. Since chloride penetrability in PC and SCM concretes is sensitive to exposure conditions, it would be reasonable to select a test method based on similar test exposure conditions as that of the concrete in the field. For example, static chloride ponding tests would be suitable for evaluating concretes to be used in submerged marine structures, and cyclic ponding tests for concretes in coastal structures that are not submerged. Further research is needed in this area of test methods and the impact of test exposure conditions on the results.

It was found in the binary concrete investigation that the cyclic chloride ponding test over 28 days from age 28 days gave results with excellent correlation to those at age 182 days for the PC and three SCM concretes evaluated. Further work is needed to verify that this test regime would give a fair assessment of characteristic chloride penetrability in concrete with different binders.

The static chloride ponding test over 91 days is considered to give reasonable results for different concretes under immersed conditions. However, for it to be suitable for quality control in concrete construction, further accelerated short term tests are preferred.

The fact, that more consistent results were observed in the tests either at later ages or after more wet-and-dry cycles is most likely connected to the more uniform moisture content in the specimens and the higher degree of maturity of the concrete. A possible approach is to accelerate both of these processes by an appropriate oven-drying procedure to precondition the specimens before a static or cyclic ponding test. For a static ponding test with this preconditioning procedure, it seems to be a "salt water absorption test"**.** However, as well as water absorption is measured by the weight gain, the chloride penetration depth can be detected by spraying silver nitrite solution onto the split specimen section. The chloride binding capacity of the cementitious binder may also be evaluated by comparison of the absorption and chloride penetration results. It is recommended, that investigations into whether such simple and accelerated tests would provide satisfactory results for the assessment of chloride penetrability in both PC and SCM concrete be carried out. Such effects as the drying temperature and time period and the possible side effects of the oven-drying process on the microstructures of different concretes need to be evaluated as well.

Although the ASTM C1202 test has the great advantage of a very short test duration,. further investigation is still warranted to verify or modify this method so that it will provide a reasonable assessment of chloride penetrability in concrete with different binders. Unless it is for a concrete that is used in submerged marine structures, the standard procedure of water-curing of specimens over 28 days in the ASTM C1202 is considered to be unrealistic. For concretes of different binders, the significance of the water curing period on the ASTM C1202 test results need to be further investigated. As well as all the above, the curing regime of the specimens in the ASTM C1202 test should be chosen to simulate the curing regime of the concrete in the field.

The chloride binding capacity of cement and cementitious materials can greatly reduce the free chloride ions in concrete; only free chloride ions cause corrosion of reinforcement in actual structures. Therefore, the way in which the impact of the chloride binding capacity of cementitious binders is evaluated in the chloride penetration tests needs further investigation.

Finally, a critical criterion to judge the suitability of a laboratory test method is the correlation of the laboratory test results with the site performance of the same concrete. A long-term test program needs to be carried out to establish a database of the performance of as many concrete mixes as possible, in both laboratory and field tests. The laboratory results of different test methods can be compared to the chloride diffusion profiles in real structures or samples under long-term natural exposure conditions.

5.2 Optimal Mix Proportions of SCM Concretes for Different Applications

In this research program, the comparisons of the performance of PC and binary or ternary SCM concretes were based on equal-mass replacements of PC, with one or two of the SCMs. The fundamental effects of w/b ratio, binder content and the replacement of PC with SCMs on the concrete properties were also evaluated. In some practical applications, however, equal-mass replacement was not necessarily the best way to achieve desired performance outcomes. Further work is needed in order to achieve the desired performance and economical benefits. The mix proportions of each type of binary and ternary SCM concrete needs to be further optimized. The results and findings of this research work have provided valuable benchmarks for the development of high performance SCM concretes for varying applications and exposure conditions. Continuing this research will also lead to the further development of systematic approaches for the selection of optimal mix proportions for SCM concretes under different exposure conditions.

5.3 Effects and Mechanisms of SCMs on Concrete Properties

Extensive research is still needed to investigate the effects of SCMs on concrete properties and the mechanisms of these influences.

It was found in this research work that some of the mechanisms used to describe the behaviour of PC concrete could not explain the behaviour of the SCM concretes. For example, the rate of bleeding of PC concrete is traditionally considered to be mostly affected by the fineness of cement particles; the finer the cement, the less bleed. However, the concretes using 35% and 65% slag cements were found to have higher bleed rates than the PC control concrete, although both of the slag cements are finer than ordinary portland cement. The bleeding of the fly ash concretes, when the PC was replaced by fly ash in equal-mass, might also be effected by factors other than the fineness of the PC and fly ash. Therefore, further investigation of bleeding in PC and SCM concrete is needed and the influences of the chemical composition and physical property of the SCMs need to be taken into account in such future analyses.

The performance of the three SCM concretes in the chloride penetration tests was found to have different sensitivities to various exposure conditions. The binary silica fume mixes were found to be sensitive to wetting-and-drying conditions, especially, when the test duration was prolonged or the tests were carried out at later ages. Under these test conditions, the silica fume mix had a much higher chloride penetrability than it did in the other tests. The fly ash mixes, on the other hand, had the opposite response to these test conditions and showed a significant reduction in chloride penetrability. It was observed in the ternary concrete investigation, that when the binder contained both silica fume and fly ash, the ternary concrete did not have such sensitivity to the cyclic ponding tests at 182 days as did the binary silica fume concrete. In the static ponding tests, the performance of the fly ash concrete was also improved more significantly than the other two SCM concretes when the immersion period was prolonged. The reasons for the different behaviours of the binary and ternary SCM concretes are not clear. Further research work is needed to investigate the mechanisms behind these phenomena. The tendency for increased chloride penetrability in silica fume concretes under the cyclic exposure conditions needs special attention. Further investigation of the effects of cyclic exposure conditions on the microstructures of silica fume concrete is recommended.

The major impact of chloride ingress into concrete is the initiation of corrosion in the reinforcing steel. It is known that only the free or mobile chloride ions are responsible for this reaction. Chloride ions in concrete can be fixed by being complexed into the mineral matrix of the binder by reaction with hydration products and by physical adsorption on the pore walls. The bound chloride ions could be up to more than 50 percent of the total chloride content in the concrete. Although the mechanisms of chloride binding in PC concrete have been studied and models proposed, the capacity and the mechanism of chloride binding in different SCM concretes are not well understood. The research results, generally suggest, that the incorporation of silica fume, fly ash or slag increases the chloride binding capacity of binders. Further research work is necessary in this area to explore the full benefits of using SCMs against chloride attack in concrete structures.

On the other hand, the threshold limitation of the chloride content in concrete for the prevention of steel corrosion is currently, in most cases, expressed in terms of the total chloride rather than the free chloride content. This is because the total chloride content can be conveniently measured from an acid-soluble chloride analysis. However, since large proportions of chloride ions are bound in concrete and not able to react with the steel, the assessment of chloride penetrability in concrete is more meaningful if it is based on the free chloride content, rather than the total chloride content. Further work is needed to develop practical test methods to differentiate the free chloride content from the total chloride content in concretes. The BRC has prepared a research proposal for further investigation in this area. The methods and techniques developed for the analysis of free chloride content can also be used for the evaluation of the chloride binding capacity of SCM concretes, as well as for the assessment of the risk of chloride-induced corrosion in existing structures.

6. SELECTED BIBLIOGRAPHY

AASHTO Designation T 259-80, "Method of Test for resistance of Concrete to Chloride Ion penetration", American Association of State Highway and Transportation Officials, Washington D.C., 1980.

ACI Committee 226, “Use of Fly Ash in Concrete”, ACI 226.3R-87, American Concrete Institute, 1987, 29 pp

ACI Committee 233, “Ground Granulated Blast-Furnace Slag as a Cementitious Constituent in Concrete”, ACI 233R-95, American Concrete Institute, 1995, 18 pp.

ACI Committee 201 (1991) “Proposed Revision of Guide to Durable Concrete”, ACI Materials Journal, 88(5), pp544-577.

Al-Amoudi, O.S.B., Rasheeduzzafar, Maslehuddin, M. and Abdujauwad, S.N. (1994) “Performance of Plain and Blended Cements in High Chloride Environments”, Paper presented at Third International Conference on Durability of Concrete, Nice, France.

ASTM C 1202-91, "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration", American Society for Testing and Materials, Feb, 1992.

Cesareni, D., and Frigione, G., “A Contribution to the Study of the Physical Properties of Hardened Paste of Portland Cements Containing Granulated Blast-Furnace Slag,” Proceedings, 5th International Symposium on the Chemistry of Cement, Cement Association of Japan, Tokyo, V.4, 1968, pp. 237-247.

Chang, Z.T., Marosszeky, M., “Chloride penetration and water absorption into PC, fly ash and slag concrete under different curing conditions”, *Durability of Concrete*, Fourth CANMET/ACI International Conference, ACI SP-170, August 17-22, 1997, Sydney, pp349-362.

Chang, Z.T., Marosszeky, M. and You-Jin Kim, “Properties of Fresh and Hardened Concrete with a Binary Binder System Containing Silica Fume, Fly Ash or Slag”, Research Report, The Building Research Centre, University of NSW, June 1998, 123pp.

Cong, X., Gong, S., Darwin, D., and McCabe, S.L. (1992) “Role of Silica Fume in Compressive Strength of Cement Paste, Mortar, and Concrete”, ACI Materials Journal, 89(4), pp375-387.

Cook, D.J. and Cao, T. (1992) “Fly Ash, Slag and Silica Fume”, Ryan, W.G. and Samarin, A. (eds), Australian Concrete Technology, Longman Cheshire Pty. Ltd, Australia.

Czernin, W. “Cement Chemistry and Physics for Civil Engineers,” Georg Godwin Ltd, London, 1980 (Translated from German edition).

Feldman, R. F., Chan, G. W., Brousseau, R. J. and Tumidajski, P. J. "Investigation of the Chloride Permeability Test", ACI Materials Journal, 91(2), May-June, 1994, pp246-255.

Fidjestøl, P. and Frearson, J. (1994) “High Performance Concrete using Blended and Triple Blended Binders”, Paper presented at ACI International Conference (Proceedings) on High-Performance Concrete, Singapore.

H. Trinh Cao, E. Mack and H. Morris, “A Review of the ASTM C1202 Standard Test ", Concrete in Australia, Oct 1996, pp23-26.

Ho, D.W.S. and Lewis, R.K. (1985) “Effectiveness of Fly Ash for Strength and Durability of Concrete”, Cement and Concrete Research, 15, pp793-800.

Hooton, R.D. (1993) “Influence of Silica Fume Replacement of Cement on Physical Properties and Resistance to Sulfate Attack, Freezing and Thawing, and Alkali Silica Reactivity”, ACI Materials Journal, 90(2), pp143-151.

Idorn, G. M., and Henriksen, K. R., "State of the Art for Fly Ash uses in Concrete," Cement and Concrete Research, V.14, No.4, July, 1984, pp. 463-470.

Johnston, C.D. (1994) "Deicer Salt Scaling Resistance and Chloride Permeability", Concrete International, 16(8), pp48-55

kanazawa, K., Yamada, K. and Sogo, S. "Properties of Low-Heat Generating Concrete Containing Large Volumes of Blast-Furnace Slag and Fly Ash," ACI SP-132, Proceedings of Fourth International Conference on Fly Ash, Silica Fume, Slag, and natural Pozzolans in Concrete, Istanbul, Turkey, May, 1992, pp. 97-117.

Malhotra, V.M. (1993) "Fly Ash, Slag, Silica Fume, and Rice-Husk Ash in Concrete: A Review", Concrete International, 15(4), pp23-28.

Malhotra, V.M. and Mehta, P. K. "Pozzolanic and Cementitious Materials", Gordon and Breach Publishers, 1996, 191 pp.

Mangat, P. S. "Influence of Fly Ash, Silica Fume, and Slag on Sulphate Resistance of Concrete", ACI Materials Journal, Sep.-Oct. 1995, pp. 542-552.

Mather, K., "Current Research in Sulphate Resistance at the Waterways Experiment Station," Sulphate Resistance of Concrete, ACI SP-77, 1982, Detroit, pp. 63-74

Neville, A. M. "Properties of Concrete," Addison Wesley Longman Limited, England, 1995, 844pp.

Nobuaki Otsuki, Shigeyoshi Nagataki, and Kenji Nakashita, " Evaluation of AgNO3 Solution Spray Method for Measurement of Chloride Penetration into Hardened Cementitious Matrix Materials," ACI Materials Journal, Nov-Dec. 1992, pp. 587-592.

Osborne, G.J. (1991) "The Sulphate Resistance of Portland and Blast-Furnace Slag Cement Concretes", Paper presented at Second International Conference on Durability of Concrete, Montreal, Canada.

Osborne, G.J. (1992) "The Performance of Portland and Blast Furnace Slag Cement Concretes in Marine Environments", Paper presented at Fourth International Conference (Proceedings) on Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, Istanbul, Turkey.

Ozyildirim, C. and Halstead, W. J. "Improved Concrete Quality with Combinations of Fly Ash and Silica Fume," ACI Material Journal, Nov-Dec, 1994, pp 587-594.

Ozyildirim, C., "Resistance to Penetration of Chlorides into Concretes Containing Latex, Fly Ash, Slag and Silica Fume", Durability of Concrete, Third International Conference, Nice, France, 1994, ACI SP-145, pp. 503 - 518.

Papadakis, V. G., Fardis, M. N. and Vayenas, C. G. "Hydration and Carbonation of Pozzolanic Cements", ACI Material Journal, Mar-Apr, 1992, pp 119-130

Papworth, F. and Grace, W. (1985) "Designing for Concrete Durability in Marine Environs", Paper presented at Concrete 85 Conference, Concrete Institute of Australia Brisbane, Australia.

Patzias, T., " Evaluation of Sulphate Resistance of Hydraulic Cement Mortars by ASTM C1012 Test Method," Concrete Durability, ACI SP-100, 1987, Detroit, pp. 2101-2120.

Pigeon, M., Garnier, F., Pleau, R. and Aitcin, P. C. "Influence of Drying on the Chloride Ion Permeability of HPC", Concrete International, Feb. 1993, pp. 65-69.

Plante, P. and Bilodeau, A. (1989) "Rapid Chloride Permeability Test: Data on Concretes Incorporating Supplementary Cementing Materials", Paper presented at Third International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete, ACI SP-114, Trondheim, Norway, Vol.1, pp.625-644.

Road Research, "Design of Concrete Mixes", D.S.I.R. Road Note No.4, London, H.M.S.O., 1950.

Roper, H., Sirivivatnanon, V. and Baweja, D. (1994) "Long-Term Performance of Portland and Blended Cement Concretes under Marine Conditions", Paper presented at Third International Conference on Durability of Concrete, ACI SP-145, Nice, France, pp.331-352.

Ryan, W.G. (1988) "Review of the Australian Experience", Paper presented at International Workshop on the Use of Fly Ash, Slag, Silica Fume and Other Siliceous Materials in Concrete, Sydney, Australia.

Sakai, K., Wtanabe, H., Suzuki, M., and Hamazaki, K. (1992) "Properties of Granulated Blast-Furnace Slag Cement Concrete", Paper presented at Fourth International Conference (Proceedings) on Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, ACI SP-132, Istanbul, Turkey, Vol. 2, pp1367-1384.

Saricimen, H., Maslehuddin, M., Al-tayyib, A.J., and Al-Mana, A.I. (1995) "Permeability and Durability of Plain and Blended Cement Concretes Cured in Field and Laboratory Conditions", ACI Materials Journal, 92(2), pp111-116

Taveres, O. (1995) "Blended Cements for Durable Concrete", Paper presented at Emerging Technologies Symposium on Cement for The 21st Century, Chicago, Illinois, U.S.A.

Torii, K. and Kawamura, M. (1992) "Pore Structure and Chloride Permeability of Concretes Containing Fly Ash, Blast-Furnace Slag and Silica Fume", Paper presented at Fourth International Conference – Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete, ACI SP-132, Istanbul, Turkey, Vol. 1, pp135-150.

Wimpenny, D. E., Ellis, C., Reeves, C. M., and Higgins, D. D. (1989), "The Development of Strength and Elastic Properties in Slag Cement Concretes under Low Temperature Curing Conditions," Proceedings of Third International Conference on Fly Ash, Silica Fume, Slag, and natural Pozzolans in Concrete, ACI SP-114, Trondheim, Norway, pp. 1288-1296.

Yamato, T., Emoyo, Y. and Soeda, M. (1983), "Strength and Freezing-and-Thawing Resistance of Concrete Incorporating Condensed Silica Fume," Proceedings of International Conference on Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, ACI SP-91, Detroit, Michigan, Vol. 2, pp. 1095-1117.