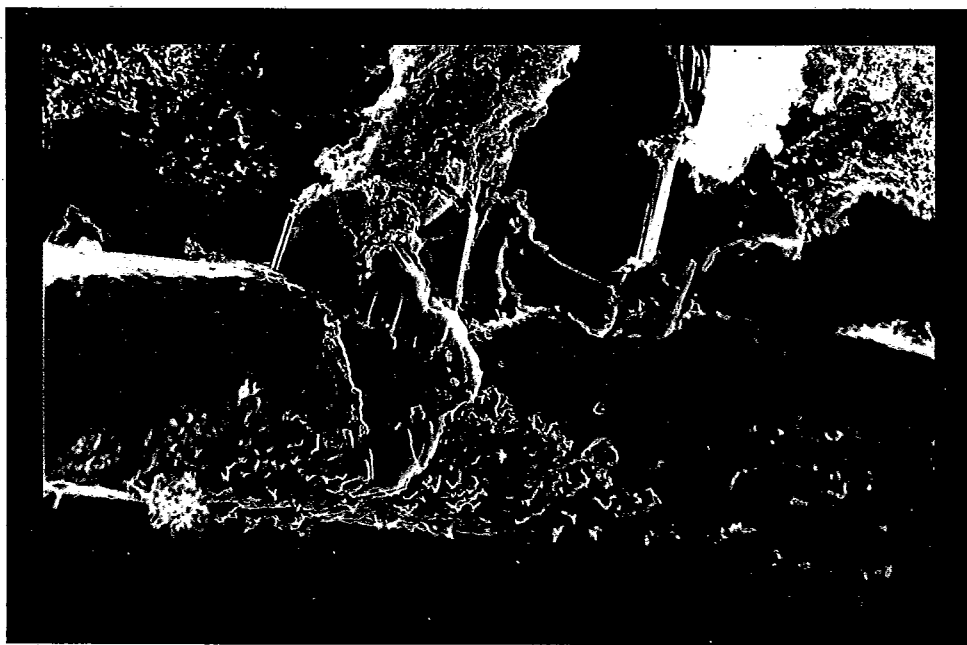


Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete

Proceedings
Fourth International Conference
Istanbul, Turkey, May 1992



Editor
V.M. Malhotra

Volume I



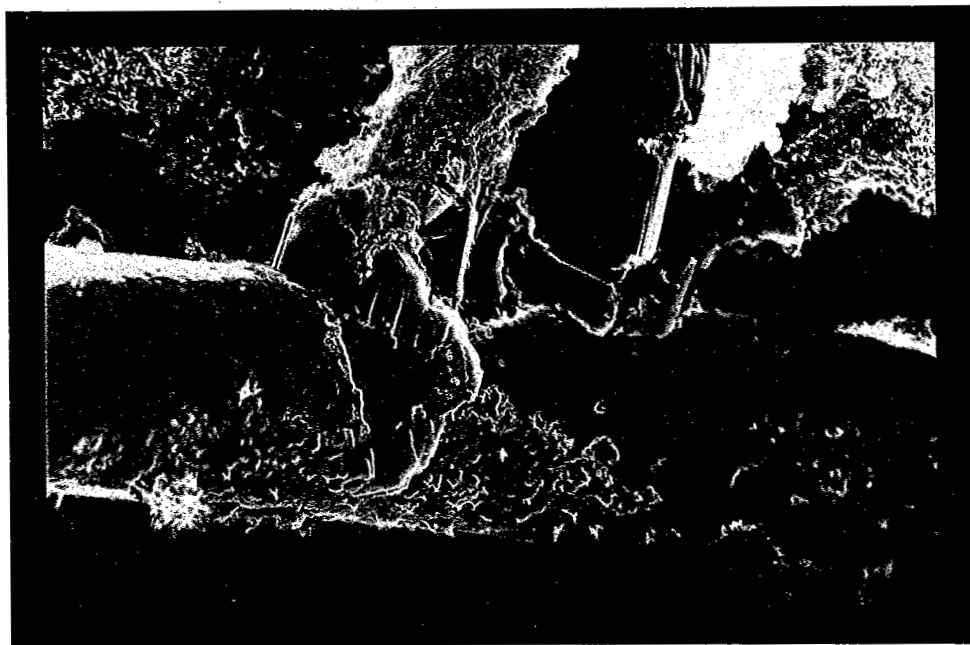
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PREFACE

The Canada Centre for Mineral and Energy Technology (CANMET) of Energy, Mines and Resources Canada, Ottawa, has played a significant role in Canada for over twenty-five years in research on fly ashes, ferrous and non-ferrous slags, and condensed silica fumes, in order to conserve both resources and energy. In July-August 1983, CANMET, in association with the American Concrete Institute and the U.S. Corps of Engineers, sponsored a five day international conference at Montebello, Quebec, Canada, on the Use of Fly Ash, Silica Fume, Slag and Other Mineral By-Products in Concrete. The main purpose of the conference was to bring together representatives from industry, universities, and government agencies to present the latest information on these materials and to explore new areas of needed research. The two volume proceedings of the conference containing sixty-two papers from fifteen countries were published as ACI Special Publication SP-79.

In 1986, CANMET, in association with the American Concrete Institute, the Canadian Society for Civil Engineering, and a number of organizations in Spain, sponsored the Second International Conference on the subject of Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete. The conference was held April 21-25, 1986, in Madrid, Spain. The two volume proceedings of the conference containing seventy-seven papers from more than twenty countries were published as ACI Special Publication SP-91.

In 1989, CANMET, in association with the American Concrete Institute, Norwegian Institute of Technology and several other organizations in Canada and Norway, sponsored the Third International Conference on the above subject. The conference was held June 18-23, 1989, in Trondheim, Norway. The two volume proceedings of the conference containing 83 papers from more than 25 countries were published as ACI Special Publication SP-114.

In 1992, CANMET, in association with the American Concrete Institute, Electric Power Research Institute, U.S.A., and several other organizations in Canada and Turkey, sponsored the Fourth International Conference on the subject. The conference was held May 3-8, 1992, in Istanbul, Turkey. More than 130 papers from 32 countries were received and reviewed in accordance with the policies of the American Concrete Institute; 89 papers were accepted for publication. To all those whose submissions

could not be included in the symposium volumes, the Institute and the Conference Organizing Committee extend their appreciation for their interest and hard work. The accepted papers were published in two volumes. The first volume contains papers dealing with fly ash and natural pozzolans, and the second volume consists of papers dealing with condensed silica fume and ferrous and non-ferrous slags. Some papers could have been published in either volume because the material covered more than one subject.

In addition to the papers which have been published in these volumes, more than 50 other papers were presented. Some of these papers were published as "supplementary papers," and the authors have been encouraged to publish them in technical journals of their choice.

Thanks are extended to those ACI members and others who helped review the manuscripts. Without their prompt review and constructive comments, it would not have been possible to publish these volumes before the conference. The cooperation of the authors in accepting reviewers' suggestions and revising their manuscripts accordingly is greatly appreciated.

The help and assistance of Mr. H.S. Wilson for administrative work associated with this publication is gratefully acknowledged. Thanks are extended to G.G. Carette for acting as the Chairman of the Slide Review Panel.

V.M. Malhotra, Editor
Chairman, CANMET/ACI
Fourth International Conference
on Fly Ash, Silica Fume, Slag
and Natural Pozzolans in Concrete

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Dedicated to all those ACI members and others
who assisted in the review of the manuscripts

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SP 132-1

Investigation into the Long-Term In-Situ Performance of High Fly Ash Content Concrete Used for Structural Applications

by M.R.H. Dunstan, M.D.A. Thomas,
J.B. Cripwell, and D.J. Harrison

Synopsis: This paper presents results of investigations carried out on high fly ash content concrete (HFCC) cores removed from a number of structures constructed in the United Kingdom since 1979.

The structures investigated were a road pavement, a major road viaduct, water-retaining and industrial structures, and a slipway subjected to marine exposure.

Concrete properties measured after ten years service, include compressive strength, depth of carbonation, permeability and chloride and sulphate penetration profiles. In addition petrographic analysis of thin sections was also undertaken.

The HFCCs studied were designed considering the fly ash to be just a further ingredient in the concrete rather than as a cement replacement. This led to higher fly ash contents and lower cement contents than is generally normal practice. The structures examined were in excellent condition after ten years. The results show a durable concrete exhibiting increases in compressive strength beyond 28 days, little evidence of carbonation, low to average permeability and resistance to chloride penetration. In this respect it is significant that at the marine exposure sites the chloride concentrations decreased significantly with depth. No evidence of alkali-silica reaction was detected in spite of reactive aggregates being present in some of the concretes.

Keywords: Alkali aggregate reactions; carbonation; chlorides; compressive strength; concrete durability; concretes; density (mass/volume); fly ash; marine atmospheres; mix proportioning; permeability; strength; sulfates; water-cementitious ratio

Dr. M.R.H. Dunstan is Principal of Malcolm Dunstan & Associates. He first conceived the concept of high fly ash content concrete in the mid 1970s and he has been closely involved with the development of this form of concrete and with roller-compacted concrete for dams for the past 15 years.

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INTRODUCTION

Up to the late 1970s concretes containing fly ash were generally proportioned by modifying traditional concrete containing portland cement, by replacing part of the cement content with an equal or greater mass of fly ash. All the concretes discussed in this paper were proportioned by taking greater advantage of the properties of fly ash, by considering the fly ash as the 'fourth ingredient' (1); that is, in addition to the aggregate, portland cement and water. The proportion of fly ash used as a cementitious ingredient of the concrete will depend upon a number of factors; in particular the strength and workability of the concrete and the 'quality', cost and water demand of the fly ash. By use of this method it is generally found that the optimum proportion of fly ash within the cementitious content of high-strength (40 MPa), high-workability (100-mm+ slump) concrete is in the order of 30 to 40%; medium-strength (20 to 30 MPa), medium-workability (50 to 75-mm slump) concrete 50 to 65%; and low-strength (10 to 20 MPa), low-workability (0-mm± slump) concrete 70 to 90%. This is a far higher proportion than is generally used in traditional fly ash concrete.

Following the introduction of the fourth ingredient concept, a number of HFCC placements were undertaken in the United Kingdom. This paper presents results of an investigation carried out to assess the condition and properties of HFCCs used in the construction of five structures after ten years service and exposure.

Details of the structures examined and the concrete mixes used are given in the paper together with results from strength, permeability and carbonation tests. In addition samples were obtained from four structures to establish the extent of chloride and sulphate penetration arising from exposure to marine and industrial environments. Petrographic analysis of thin sections was also undertaken to establish if alkali-silica reaction was present.

Details of mixture proportions used for each placement are given in Table 1 together with the appropriate 28-day characteristic strength¹ requirement. Table 2 shows the typical physical and chemical properties of the fly ashes used for each placement.

HISTORICAL BACKGROUND TO HFCC PLACEMENTS

Didcot Power Station Coal-Stocking Area

In 1981, the coal-stocking area of Didcot Power Station was extended. An area for stockpiling coal was required, surrounded by a road to take heavily-loaded scrapers and tracked dozers. The Owner, the Central Electricity Generating Board (CEGB), determined that it would be an ideal area for a full-scale working trial of the concept of HFCC concrete. The coal-stocking area (see Figure 1) was created by placing a concrete conforming to the Department of Transport Specification for a sub-base (2); essentially a concrete with a minimum density of 95% of the theoretical-air-free density and with a 28-day cube compressive strength of 10 to 20 MPa. This concrete was placed with a paver-finisher without the roller compaction normally associated with this form of concrete. The concrete contained an oolitic limestone aggregate and the C_f (fly ash/cementitious ratio by volume) was 0.80, and C_w (water/cementitious ratio by volume) was 1.00 (water/cementitious ratio by weight 0.44). Cores taken at an age of 28 days were found to have an average equivalent cube compressive strength (3) of 23.7 MPa compared to the average of 16.3 MPa of

¹ The characteristic strength is the minimum strength with an allowable failure rate (in the case of the structures in this paper 5%)

cubes manufactured from concrete in the areas at which the cores were taken.

Two different pavement-quality (PQ) concretes were designed for the roads surrounding the coal-stocking area to conform to a characteristic flexural strength of 4 MPa at an age of 28 days (PQ(28)) and 91 days (PQ(91)). Both concretes were used in 225-mm thick unreinforced slabs founded on a 125-mm thick HFCC sub-base - the latter had similar properties to the coal-stocking area although the performance was slightly inferior to that of the former. Both PQ concretes contained a crushed carboniferous limestone and the C_f of the PQ(28) was 0.60 and of the PQ(91) 0.65. The C_w s were 0.95 for the PQ(28) (water/cementitious ratio by weight 0.37) and 0.91 for the PQ(91) (water/cementitious ratio by weight 0.36).

After completion of the coal-stocking area, it was decided to change the purpose to a parking area for all the heavy plant used at the station as it had an excellent finish (see Figure 2). During the ten years that the area has been in service, both the 'parking' area and the roads have performed extremely well with the original surface finishes being clearly visible (see Figure 3).

Didcot Power Station Oil Tank Storage Area

In April 1982, bids were invited for the construction of an oil tank base and surrounding retaining wall. The foundation of the oil tank consisted of a circular 450-mm thick reinforced concrete slab containing 230 m³ of concrete which was required to be placed in one operation. After discussion with the Owner the successful Contractor offered an alternative providing HFCC for the foundation slab. This was the first use of HFCC in a structural environment. The 30-MPa concrete contained the same oolitic limestone as the coal-stocking parking area and the C_f was 0.60 and C_w 0.95 (water/cementitious ratio by weight of 0.35). The concrete in the foundation slab appeared to have a low slump, being quite cohesive, but was readily pumpable and very easily compacted. The concrete conformed to the 30-MPa strength requirements without difficulty.

After the successful placement of the foundation slab, the Contractor requested permission to construct the retaining walls with the same concrete. This was accepted by the Owner. A 'sawn-board' finish was specified for the outside face of the walls. The HFCC provided an excellent finish on both faces.

Since completion some nine years ago, the finish on the external face has hardly deteriorated and is still in excellent

condition (see Figure 4). In addition, the same concrete has been used for numerous other contracts in the area and has become the 'standard' structural concrete for use in this Power Station.

Mumbles Slipway

In the summer of 1983, two new slipways were being constructed for the City of Swansea at Mumbles. The Contractor offered an alternative to the original design of a 200-mm thick roller-compacted concrete (RCC) base and a 300-mm thick immersion-vibrated surface concrete. Both concretes were to be HFCC. This was accepted by the Owner after trial mixes. Both concretes were designed for a characteristic strength of 30 MPa, but more significantly were designed to be sufficiently cohesive so that they would not be damaged when immersed by sea water soon after placement. Both concretes contained sea-dredged sands which might have been susceptible to alkali-silica reaction (ASR). The coarse aggregate was a crushed carboniferous limestone. The roller-compacted concrete base had a C_f of 0.60 and a C_w of 1.09 (water/cementitious ratio by weight of 0.41) and the 30-mm slump concrete in the surface of the slipway had the same C_f but a C_w of 0.97 (water/cementitious ratio by weight of 0.37).

The Mumbles site has some of the largest tidal variations in the U.K. - the range from high springs to low springs being 10 m. Due to difficulties at the ready-mix plant which was 15 kms from the site, the delivery of some of the RCC was delayed and it was roller compacted just in front of the incoming tide. At the time, it was thought that the concrete would have to be removed at the next low tide. However, on subsequent inspection it was found to be in remarkably good condition and seemed to be undamaged by the very early immersion in sea water.

Since completion, the slipways have performed extremely well and there has been little visible deterioration of the surface of the concrete (see Figure 5).

Wincanton Sewage Treatment Works

In the summer of 1984, a contract was awarded by the Wessex Water Authority for the construction of new sewage treatment works at Wincanton in Dorset. The successful Contractor was the same that had constructed the Didcot oil-tank foundations and retaining wall. The local aggregates at the

site were suspected of being susceptible to ASR and the 25-MPa concrete was specified as having a high resistance to sulphate attack. In addition, there was no ready-mix plants near the site. Following successful use of HFCC at Didcot, the Contractor offered the Owner the alternative of site-batched HFCC for all the concretes at the sewage treatment works. After laboratory trial mixes, the offer was accepted.

The concrete contained a water-reducing admixture, had a C_f of 0.625 and C_w of 1.10 (water/cementitious ratio by weight 0.43). Following plant trials to prove the mix, the concrete was used for all placements on the site. The concrete placement was very successful because the construction crew found the material very easy to handle and use. A considerable number of tanks were involved in the contract and all passed their water test the first time. As with Didcot placements, the finish was excellent (see Figure 6). During the contract, there was a miners' strike in the U.K. and the first-choice fly ash became unavailable. A fly ash from a different Power Station then had to be used. Although the standard deviation of the concrete was fairly high, the concrete at all times conformed to the requirement of a characteristic strength of 25 MPa.

Grangetown Link

The Grangetown Link forms part of the southern circular road of Cardiff in Wales. It contains the longest pre-cast post-tensioned concrete viaduct in the U.K. (see Figure 7) and the Cogan Bridge, which forms part of the project, is the longest pre-cast post-tensioned concrete bridge in the U.K.. There were 12 different concretes required for the project, although four of these formed the bulk of the concrete used. These were:-

1. 52.5/20 - this concrete was used in the manufacture of 928 pre-cast concrete elements and had a characteristic strength of 52.5 MPa and a specified slump of 65 to 135 mm. Some of this concrete was designed for placement elsewhere in the contract by pump. The total volume was 19 000 m³.
2. 37.5AE/20 - this concrete had a characteristic strength of 37.5 MPa, was air entrained (specified range 3.0 to 6.0%) and had a specified slump within the range of 50 to 100 mm.
3. 37.5S/20 - this 'flowing' concrete was used in the piles and had to be self compacting. The characteristic strength was 37.5 MPa and the slump was required to be in the range of 100 to 200 mm. The total volume was 12 000 m³.

4. 30/20 - this concrete had a characteristic strength of 30 MPa and the slump was required to be in the range of 50 to 100 mm. The total volume was 22 000 m³.

Although fly ash was not precluded from use in the concrete, the Specification did not allow it to be included in the cementitious content and minimum cement contents were specified in line with the Department of Transport Specification (2). For example the 52.5/20 mix had to have a minimum cement content of 405 kg/m³ and the 37.5AE/20, the 37.5S/20 and the 30/20 concretes were required to have a minimum content of 335, 335 and 315 kg/m³ respectively.

The coarse aggregate was a crushed carboniferous limestone and the fine aggregate was dredged from the Bristol Channel. Soon after the award of the contract, it was suggested that the fine aggregate might be susceptible to ASR and consequently it was considered prudent to limit the maximum alkali content in the concrete to 3 kg/m³ in line with the recommendations of the Concrete Society at that time (4). Unfortunately the local portland cement had a relatively high alkali content and the maximum allowable cement content (in order to keep within the specified alkali content) was 330 kg/m³. This was both below the specified minimum cement content of the majority of mixes and was insufficient in order to obtain the characteristic strength of the 52.5/20 concrete. Consequently the Contractor proposed that the mixes should be designed containing fly ash as part of the cementitious content. Although the mixes were not proportioned to optimise the fly ash content, it was agreed that the minimum portland cement content could be reduced to 350 kg/m³ for 52.5/20 concrete and to 290 kg/m³ for the 37.5AE/20 concrete investigated in this paper.

PROPERTIES OF HFCC AFTER 10 YEARS

Sampling and Test Procedure

A number of 100-mm nominal diameter cores were removed from each structure at locations agreed with the Owner. In addition to the cutting of cores, samples of concrete were also obtained from three structures by drilling the concrete with a 13-mm dia. masonry bit in a rotary hammer drill. Powdered concrete samples were collected to depths of up to 31 mm in increments of 5 to 6 mm.

The concrete cores were cut by diamond saw in the laboratory to produce suitable specimens for the following tests:

density, percentage voids, compressive strength, depth of carbonation and permeability. Thin sections were prepared for petrographic analysis.

The density, percentage voids and compressive strength tests were carried out in accordance with the relevant parts of BS1881 (3). The depth of carbonation was determined by spraying freshly-fractured surfaces of concrete specimens with phenolphthalein indicator. Oxygen permeability of 50-mm thick surface samples were determined using a permeability cell developed by Lawrence (5). The coefficient of permeability was obtained using a combination of Darcy's Law and the Poiseuille equation. The powdered concrete samples were subjected to determinations of chloride and sulphate contents using X-ray fluorescence analysis.

Visual Examination of Cores

Detailed visual examinations were carried out on all cores subjected to compressive strength testing. The concrete in all cores was well compacted and showed an even distribution of materials. Where steel reinforcement was removed with the concrete cores, there was no apparent signs of steel corrosion.

Results of Laboratory Tests

Saturated-surface-dry densities were calculated for each core and are shown in Table 3. The compressive strength of the concrete cores, corrected to equivalent cube strength (3), are also shown in Table 3 together with percentage voids. The relatively low void content confirms that the concretes were well compacted at placement.

The results of carbonation depth measurements are shown in Table 4. With the exception of the Didcot retaining wall, mean carbonation depths are low in individual cores and compare with those levels reported for 'traditional' fly ash concrete (6).

Reacted and un-reacted fly ash particles were found in all the samples. The distribution of fly ash particles was even and the average size was approximately 30 μm , although some particles of 150 μm diameter were also found.

To determine whether alkali-silica reaction had occurred, thin sections were examined for signs of internal cracking of the aggregate, cracking at the aggregate-matrix interface, gel

presence in voids and cracks, reaction rims and discolouration of the cement paste near particles. Few cracks were found in any of the samples and these were typical of specimen preparation and were not associated with any particular aggregate type. No gel was found in the cracks. Chert, flint and greywacke particles (which are known to be alkali reactive) were found in some of the samples, but in all cases no evidence of ASR was detected.

The coefficients of oxygen permeability of the specimens tested are shown in Table 5. The results lie within the range reported (7) for concretes with low to average permeability values. In addition, the values compare with those reported (6) for traditional fly ash concrete.

The results of the analyses carried out on powder samples to determine chloride and sulphate concentrations are shown in Figures 8 and 9 respectively. The chloride and sulphate, as SO_3 , are expressed as a percentage of the total cementitious content of each HFCC placement investigated, using the proportions of cement and fly ash as shown in Table 1. It can be seen that both chloride and sulphate contents decrease with depth particularly so for the Mumbles placement.

It should be further noted that the concrete used at Mumbles was placed between tides and subjected to immersion by sea water shortly after placement. Moreover, the concrete has continued to be subjected to the effects of two tides per day for eight years.

Discussion

The five placements reported in this paper provided an excellent opportunity to assess the properties of HFCC after up to ten years in service. Mix design information is available together with details of the development of compressive strength up to an age of 28 days. In addition by reference to published work (6), comparisons with respect to carbonation, permeability and chloride penetration can be made with traditional fly ash concrete.

Figure 10 shows mean 28-day and 10-year($\pm$) compressive strengths for each of the five placements investigated. Whilst there are differences in the percentage increase in compressive strength beyond 28 days, it can be seen that each concrete exhibits a continuing upward trend. This feature is particularly noticeable at Mumbles and Wincanton, which show increases approaching 50%.

With the exception of the Didcot retaining wall placement, depths of carbonation measured for HFCC were low (see Table 4). Mean values range from 1 to 3 mm. Generally these results confirm that HFCC is no more susceptible to the effects of carbonation than traditional portland cement and fly ash concretes designed for equivalent strength (6).

The relatively low permeability of HFCC (see Table 5) accords with that of traditional fly ash concrete and can be explained as follows; firstly the reduced water content of HFCC will result in a smaller number of large pores when compared with a portland cement concrete; secondly, the pozzolanic reaction between the fly ash and calcium hydroxide, released by the hydrating portland cement, results in the production of hydration products which may block pores leading to a finer pore structure (6). In this respect the characteristics of HFCC are comparable with traditional fly ash concrete providing similar benefits by reducing the permeability of the concrete.

The permeability of concrete is a crucial parameter in determining durability as it provides a measure of the concrete's ability to resist the penetration of carbon dioxide, sulphates and chlorides. Despite high surface concentrations of chlorides, the levels at the reinforcing steel were found to low in all tests. The reductions in concentrations with depth are a consequence of the low permeability of HFCC.

No evidence of ASR activity was detected in any of the samples.

CONCLUSIONS

The philosophy of treating fly ash as a fourth ingredient, and as a cementitious component of concrete, appears to be well founded from the results obtained in this investigation. The percentage increase in compressive strength from 28 days, while varying between placements, indicated the continuing contribution of fly ash to long-term strength development.

No ASR activity was found despite susceptible aggregates being present.

Low depths of carbonation (with one exception) and low to average permeability coefficients indicate that the HFCC provides good quality cover to steel reinforcement. HFCC subjected to aggressive sea water exposure has provided adequate resistance to the penetration of chloride ions and the

chloride concentrations found at the level of the reinforcing steel are within the limits recommended.

The results obtained in this investigation show that HFCC can be used successfully in structural concrete applications and in conditions exposed to sulphate and chloride attack. In consequence, the limits on fly ash content of 25 to 35% (by weight of cement) in certain Specifications may be judged conservative.

ACKNOWLEDGMENTS

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TABLE 1--DETAILS OF HFCC MIXES USED

Concrete	28-day characteristic compressive strength (MPa)	portland cement	fly ash	Mixture proportions (kg/m ³)					water (litres)	WRA ⁽¹⁾ (litres)	AEA ⁽²⁾ (litres)
				coarse agg.	fine agg.						
Didcot PQ(28) Flex. str.	4	205	212	1055	760	155	-	-			
Didcot PQ(91) Flex. str.	4	175	225	1400	760	146	-	-			
Didcot OTS	30.0	245	250	945	685	184	-	-			
Mumbles ⁽³⁾	30.0	166	182	1310	635	142	-	-			
Wincanton	25.0	176	206	1120	715	163	1.3	-			
Grangetown	37.5	290	140	1165	630	150	2.0	0.4			

Notes:-

1. Water-reducing admixture (plasticiser)
2. Air-entraining agent
3. Immersion-vibrated surface concrete

TABLE 2--TYPICAL PHYSICAL AND CHEMICAL PROPERTIES
OF FLY ASHES USED IN THE VARIOUS PLACEMENTS

	Didcot	Mumbles	Wincanton ⁽¹⁾		Grangetown ⁽²⁾		
<i>Physical properties (%)</i>							
Retained on 45- μ m	19.0	7.2	19.0	14.7	14.7	6.1	12.3
Loss on ignition	5.0	2.7	5.0	2.9	2.9	2.2	2.2
<i>Chemical properties (%)</i>							
SiO ₂	48.6	49.8	48.6	48.5	48.5	49.4	51.0
Al ₂ O ₃	28.1	29.0	28.1	27.7	27.7	31.1	29.5
Fe ₂ O ₃	10.9	11.7	10.9	11.2	11.2	9.4	6.9
CaO	4.6	1.6	4.6	4.5	4.5	3.1	4.1
MgO	1.6	1.5	1.6	1.6	1.6	2.2	1.4
Sulphate as SO ₃	0.77	0.81	0.77	0.79	0.79	0.57	0.85
Na ₂ O ⁽³⁾	1.3	1.3	1.3	1.1	1.1	0.9	1.5
K ₂ O	3.0	3.8	3.0	2.8	2.8	2.7	3.5
TiO ₂	1.1	1.0	1.1	1.1	1.1	1.0	1.1

Notes:-

1. Two sources of fly ash used
2. Three sources of fly ash used
3. Acid-soluble sodium

TABLE 4--DEPTH OF CARBONATION AS MEASURED ON CONCRETE CORES

Location	Cores tested (N ^o)	Range of carbonation depths (mm)	Mean carbonation depth (mm)
Didcot PQ(28)	2	1 - 3	2
Didcot PQ(91)	2	2 - 3	3
Didcot OTS	4	5 - 20	11
Mumbles	7	1 - 2	1
Wincanton	8	1 - 4	2
Grangetown	3	1 - 2	1

TABLE 3--DENSITY AND STRENGTH DATA
AS MEASURED ON CONCRETE CORES

Location	Specimen N ^o	Density (kg/m ³)	Voids (%)	Cube strength		Standard deviation (MPa)
				Equivalent	Mean	
Didcot PQ(28)	D8	2340	1.0	46.7	43.7	5.87
	D9	2340	1.0	47.6		
	D10	2321	1.5	37.0		
Didcot PQ(91)	D5	2344	0	49.4	46.9	4.23
	D6	2345	1.0	40.7		
	D7	2360	1.0	50.1		
Didcot OTS	D1	2269	0.5	50.4	45.3	4.86
	D2	2270	1.0	40.7		
	D3	2241	0	44.9		
Mumbles	M1	2398	0	52.3	61.1	6.47
	M2	2423	0.5	60.7		
	M3	2435	0	71.5		
	M4	2412	0.5	60.1		
	M5	2401	1.0	64.7		
	M6	2450	0.5	56.8		
Wincanton	W1	2358	0.5	69.4	66.2	5.80
	W2	2343	1.0	58.5		
	W3	2372	1.0	71.2		
	W4	2374	1.0	75.2		
	W5	2356	1.0	67.9		
	W6	2319	1.5	61.8		
	W7					
	W8					
	W9	2397	0.5	65.5		
	W10	2398	0	60.1		
Grangetown	G1	2423	0.5	66.7	66.0	4.33
	G2	2410	0.5	61.4		
	G3	2441	0.5	70.0		

TABLE 5--COEFFICIENTS OF OXYGEN PERMEABILITY
AS MEASURED ON CONCRETE CORES

Location	Cores tested (N ^o)	Range of permeability (x 10 ⁻¹² m ²)	Mean permeability (x 10 ⁻¹² m ²)
Didcot PQ(28)	2	13.2 - 158.6	86
Didcot PQ(91)	2	1.6 - 2.7	2.2
Didcot OTS	4	37.4 - 124.9	77
Mumbles	7	2.2 - 5.3	4.2
Wincanton	8	6.5 - 18.2	9.3
Grangetown	3	6.8 - 14.7	10.3



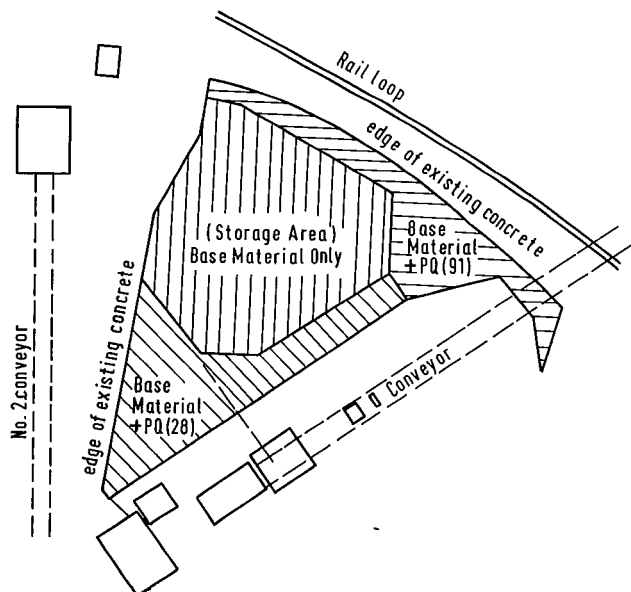


Fig. 1--Location of the various concrete areas at the Didcot coal-stocking area



Fig. 2--Photograph of "parking area" at Didcot coal-stocking area

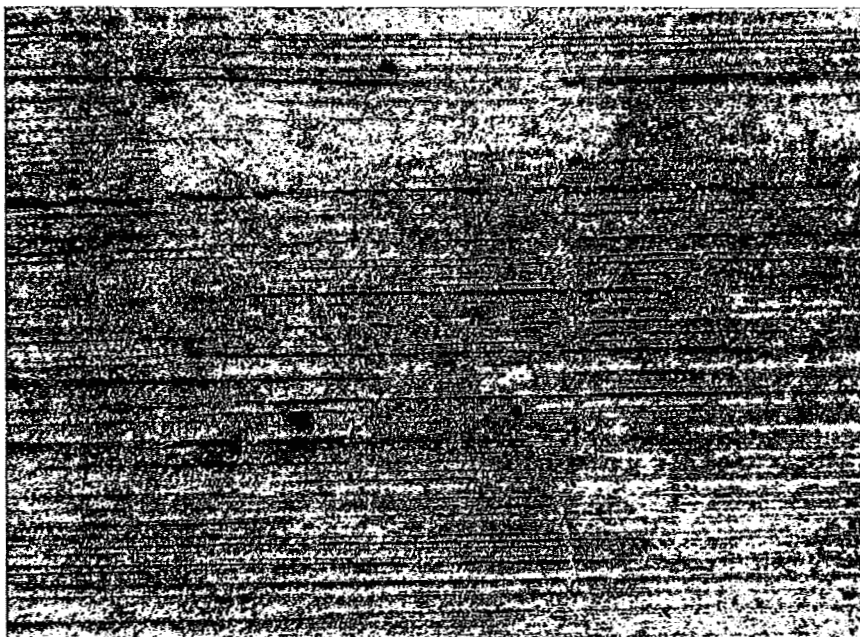


Fig. 3--Photograph of surface finish of heavy-duty road around Didcot coal-stocking area



Fig. 4--Photograph of "sawn-board" finish on external face of the retaining wall at Didcot oil-storage area



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Fig. 5--Photograph of slipway at Mumbles

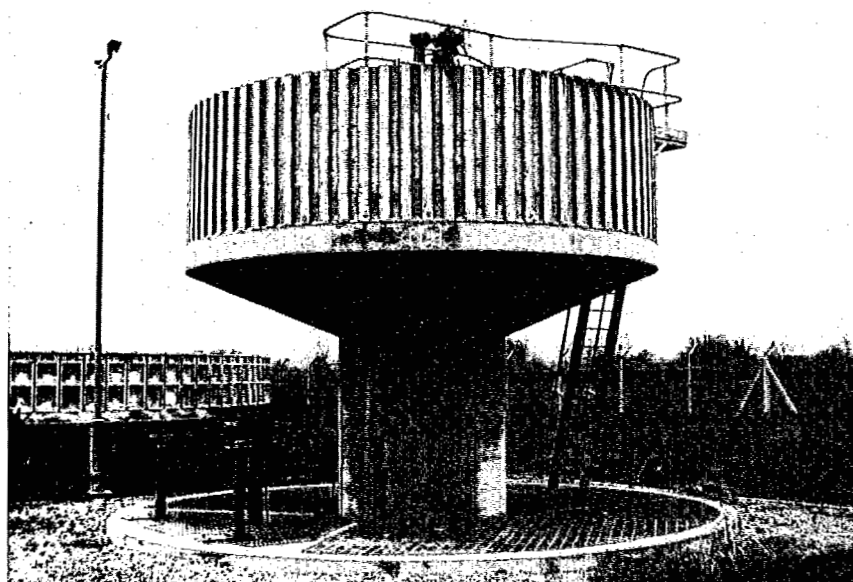


Fig. 6--Photograph of inlet tower at Wincanton Sewage Treatment Works

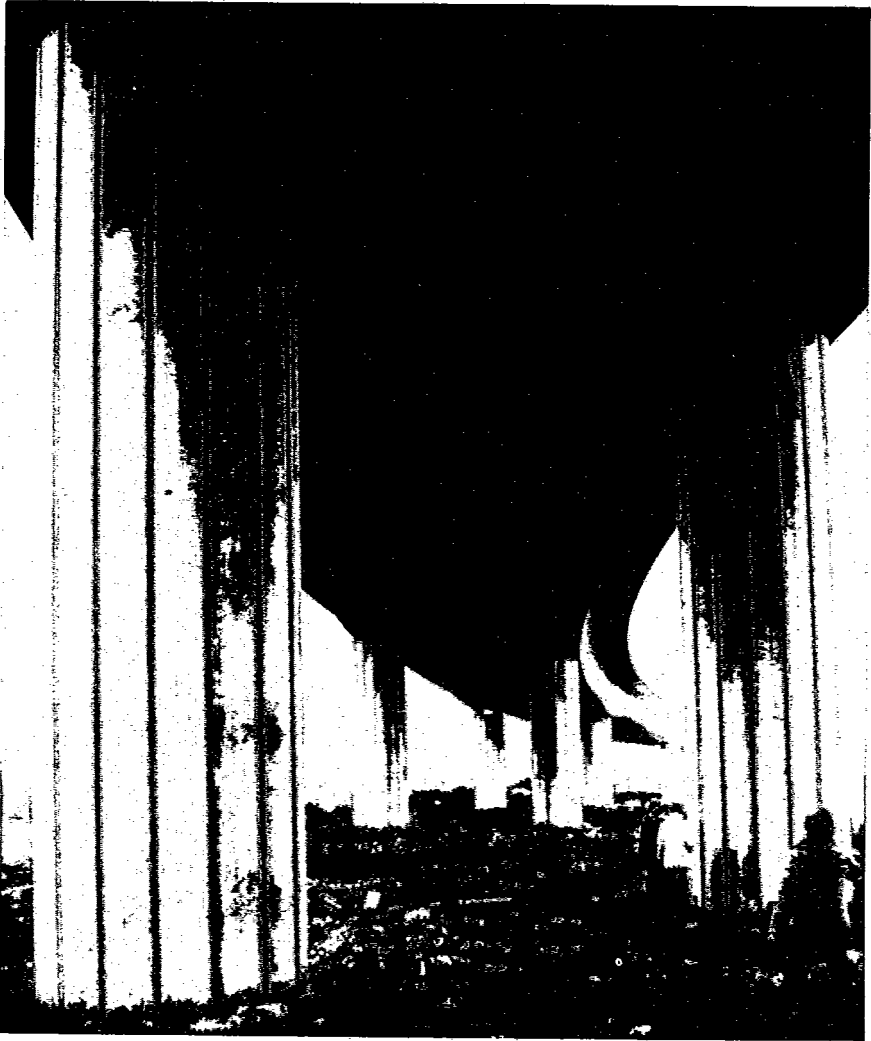
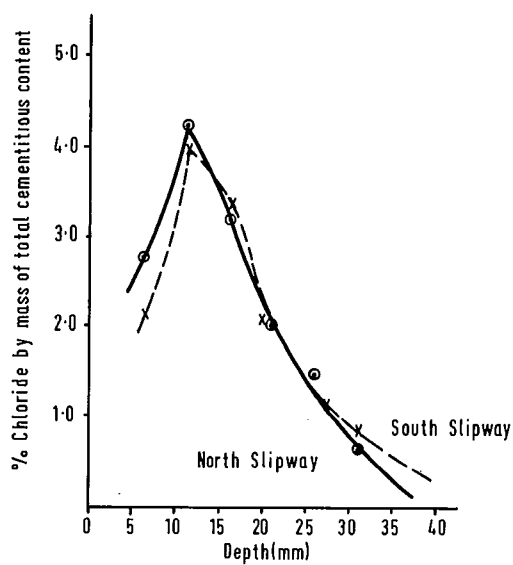
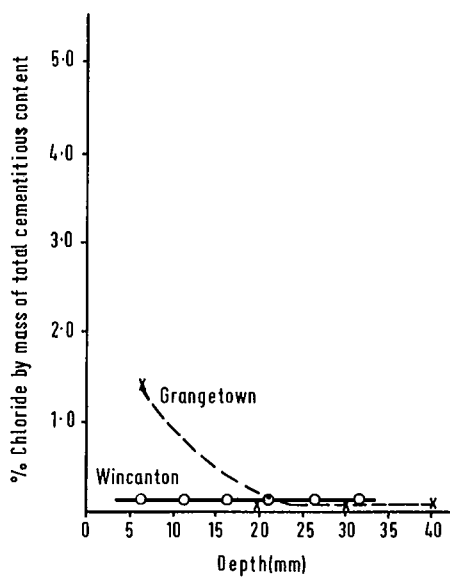


Fig. 7--Photograph of precast post-tensioned concrete viaduct at Grangetown Link

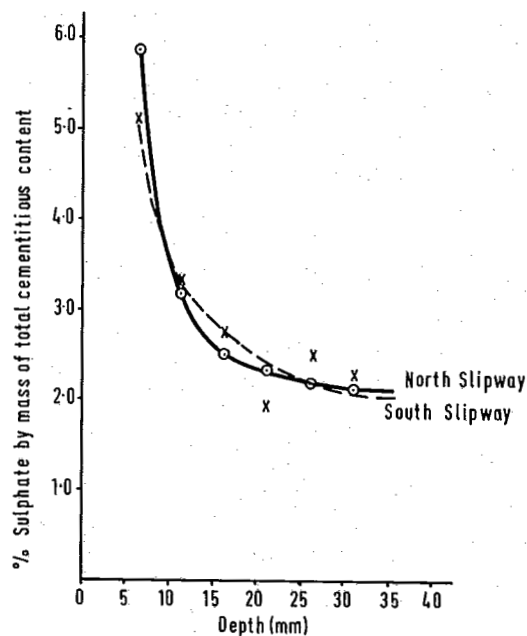


a) Mumbles placement

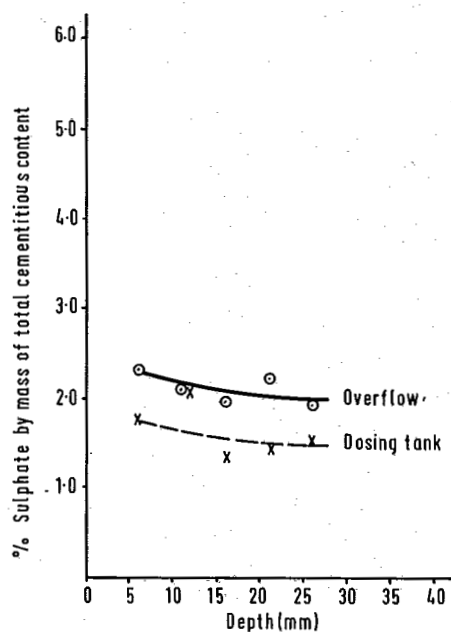


b) Wincanton and Grangetown placements

Fig. 8--Chloride profiles measured on concrete cores



a) Mumbles placement



b) Wincanton placement

Fig. 9--Sulphate profiles measured on concrete cores

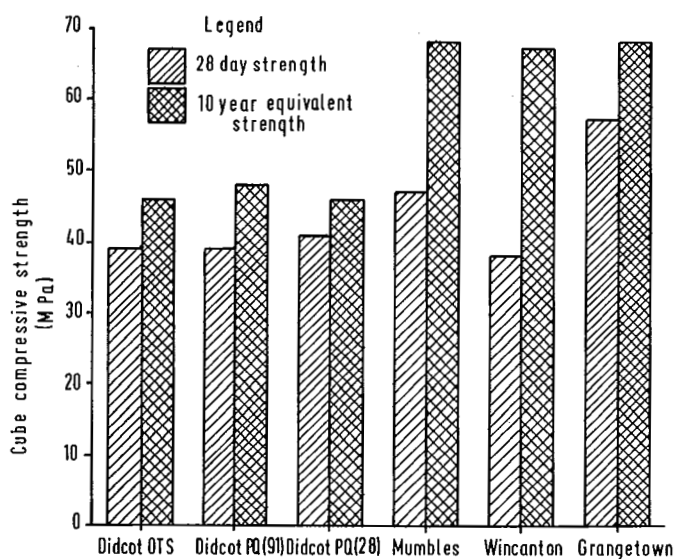


Fig. 10--Development of compressive strength between 28 days and approximately 10 years

SP 132-2

Influence of Residual Carbon in Fly Ash on Microstructure and Strength Development of Mortars and Concretes

by H. Hornain, F. Miersman,
and J. Marchand

Synopsis: The effect of residual carbon content in fly ash on the hardened cement paste properties was investigated. Mortars and concretes were prepared with three different aluminosilicate type fly ashes of the same mineralogical composition but containing respectively 5, 7 and 12% of residual carbon. Mixtures containing 15 and 30% of fly ash, as replacement of cement, were studied. The microstructure was studied by means of SEM observations and EDS analysis. Pore size distributions were determined by mercury intrusion porosimetry. Compressive and flexural strengths were measured after 2, 7, 28 and 90 days. Results indicate that the residual carbon content in fly ash does not have any detrimental influence on the microstructure and on the mechanical strength development even at the highest carbon content.

Keywords: Carbon; compressive strength; flexural strength; fly ash; microstructure; porosity; scanning electron microscope; strength

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INTRODUCTION

In the past decade, the addition of fly ash in concrete has become common practice. Besides its economical advantages, the partial replacement of cement by pozzolanic aluminosilicate type fly ashes (or Class F according to ASTM) in concrete is known to have a beneficial effect on several properties of both fresh and hardened concrete [1, 2, 3]. In many cases, the use of fly ash tends to improve the workability and cohesion of fresh concrete, at a given slump, and significantly reduces bleeding. Similarly, some fly ashes significantly decrease the water demand of concrete and consequently increase the density of the cement paste [4, 5, 6].

A product of the combustion of anthracite and bituminous coals, the aluminosilicate type fly ash often contains residual carbon particles. The quantity of carbon is generally determined by the loss on ignition which provides a rough estimate of the true value. In many countries, the loss on ignition of fly ash is limited by the standard specifications to values in the 5 to 12% range [7, 8, 9].

A high carbon content is reported to have a detrimental influence on certain concrete properties. Besides their effect on the color of concrete, carbon particles tend to dramatically reduce the efficiency of air-entraining admixtures in concrete. In recent years, this effect has been widely investigated [10, 11, 12, 13]. Test results indicate that a proper air bubble network can however be achieved by increasing the admixture dosage or by using special air entraining agents [14]. It also appears that carbon contents up to 23% do not adversely affect the freezing and thawing resistance of concrete as long as adequate spacing factors are obtained [10]. Regarding the effect of carbon content on the electrical resistivity of concrete and on the corrosion of steel reinforcement, test results reported by Rasheeduzzafar et al. [15] show that, because of the low amount and good dispersion throughout the cement paste, carbon particles do not significantly influence the behavior of concrete.

Residual carbon in fly ash is reported to increase the water requirement of concrete and therefore influence the mechanical strength adversely [6]. However, according to results presented by Osbaeck [13, 16], the water addition necessary to maintain a given flow does not lead to a strength decrease because carbon particles have a compensating air-reducing effect. Previous investigations have also indicated that the presence of relatively high amounts of carbon in fly ashes (up to 19% in certain cases) did not affect the compressive strengths of mortars and concretes [5, 17, 18].

The purpose of the present investigation is to bring further information on the effect of residual carbon in fly ashes on microstructure and strength development of mortars and concretes.

MATERIALS AND EXPERIMENTAL PROCEDURES

Three fly ashes containing respectively 5, 7 and 12% of residual carbon, as determined by loss on ignition, were selected. The fly ashes with 5% and 12% came from different productions of the same plant. The fly ash with 7% carbon was prepared by mixing the two others. Except the loss on ignition, all fly ashes had the same chemical composition. The mineralogical composition of each fly ash was determined by X-ray diffraction analysis and by optical microscopic observations. In order to evaluate the homogeneity of each load, several samples of each ash were analyzed. Results indicated that, in all cases, the homogeneity was satisfactory and that the three fly ashes had similar mineralogical compositions. Blended cement were prepared by replacing respectively 15% and 30% (by mass) of ordinary Portland cement (OPC) by each of the fly ashes. The chemical compositions of the OPC and of the fly ashes are given in Table 1 and their physical properties appear in Table 2. The mineralogical compositions of the three fly ashes, as determined by X-ray diffraction, are given in Figure 1.

The morphologies of residual carbon particles present in the fly ashes were characterized by scanning electron microscopic (SEM) observations. As can be seen in Figures 2, 3 and 4, different morphologies were observed: large massive particles (Figure 2), particles surrounding very microspheres of fly ash (0,1 to 2 μm), described as "Swiss cheese" particles by Diamond [19] (Figure 3) and clusters of microspheres partially held together by residual carbon films (Figure 4).

Since trial batches had indicated that the fly ashes used in this investigation had no significant effect on the workability of fresh concrete, it was decided to prepare all mortar and concrete mixtures with a constant water/(OPC+fly ash) ratio. Mortar prisms (4x4x16 cm) and concrete cylinders (16x32 cm) were cast according to the A.F.N.O.R. standards [20, 21]. Mortar and concrete mixture proportions are given in Table 3 and the slumps of all concrete mixtures appear in Table 4.

After demoulding, all mortar and concrete samples were stored in tap water at 20°C until testing. Compressive strengths of mortars and concretes, and flexural strengths of mortars were measured at 2, 7, 28 and 90 days. The influence of the carbon content on the microstructure of mortars was studied by SEM observations and EDS analysis. Pore size distributions of all mortar mixtures were determined by mercury intrusion porosimetry after 28 days of curing. For

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each mixture, two samples were intruded. All samples were D-dried before the test. A contact angle of 140° was assumed in all cases.

TEST RESULTS AND DISCUSSION

Compressive and flexural strength

The compressive and flexural strength results of mortars are given in Tables 5 and 6. The strength development of mortars is also illustrated by Figure 5. As expected, the flexural and compressive strengths of the blended cement samples were lower than that of the OPC specimens. The differences decreased, however, with time and became less at 90 days. The influence of a fly ash on the strength development can be related to its pozzolanic activity and, according to Feret's law, to the increase of the absolute volume of solids. Strength comparisons between the different blended cements do not indicate any detrimental effect of the carbon content in fly ash. Interestingly, compared to the OPC and the blended cement with 5% carbon fly ash, blended cements with the higher carbon contents (i.e. 7 and 12%) showed somewhat higher strengths. This can be attributed to two different factors. Firstly, the 12% carbon fly ash was much finer than the 5% carbon fly ash. The 7% carbon fly ash, which is a blend of the 5 and 12% carbon fly ashes, is also finer than the 5% carbon fly ash. Increasing the fineness leads to an increase in the pozzolanic activity of the fly ash. Secondly, carbon particles might have acted as an air-reducing agent which had a beneficial effect on the mechanical strength.

The same conclusions can be drawn from the compressive strength results obtained with concrete mixtures. These results are given in Table 7 and illustrated by Figure 6. An increase of the compressive strengths with time can be observed. After 90 days, the strengths of all blended cements were at least 85% of that of the OPC concrete. As for the mortar mixtures, the high carbon content of the fly ash did not appear to have any detrimental influence on the concrete mixtures.

Pore size distributions

The mercury intrusion porosimetry measurements confirm the above observations. The results are given in Table 8 and are illustrated in Figure 7. The total pore volume appear to be higher for the blended cement samples. Pore size distributions indicate, however, a displacement towards the smaller radius for the blended cement mortars. The comparison between the three mortars made with the blended cements containing 30% of fly ash showed a decrease of the total pore volume with increase of the carbon content. This can be attributed to the already mentioned effects: higher activity of the finer fly ash containing 12% of carbon particles, and an air-reducing effect of carbon. The total pore volumes correlate well with compressive strength values as illustrated in Figure 8 where results of the present study and another investigation (with different mortar mixtures than those reported here) are plotted.

Microstructure

The SEM observations of mortars did not show any detrimental effect of the residual carbon content in fly ash. Examinations of fractured surfaces do not easily reveal the presence of residual carbon particles. As can be seen in Figures 9 and 10, the bond between fly ash and the cement hydration products appears, in general, to be rather good. Fly ash particles seem to have well reacted although calcium hydroxide crystals are still apparent. Calcium monosulfo-aluminate crystals can also be observed. This results are consistent with the findings of other researchers.

CONCLUSION

The results of this study show that carbon content of fly ash, up to 12%, did not have any detrimental effects on the strength development and on the microstructure of mortars and concretes. From the standpoint of strength development, the fineness of fly ash seems to be, at least, as important as the carbon content. These results are in good agreement with previous published findings of other researchers which indicate good physical and chemical behavior of such fly ashes in well designed and well cured concretes.

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TABLE 1--CHEMICAL COMPOSITION OF THE FLY ASHES AND THE OPC

Constituents	Fly ash (%)			OPC (%)
	FA 5% C	FA 7% C	FA 12% C	
Silicon dioxide (SiO ₂)	51.68	50.70	48.10	23.31
Aluminium oxide (Al ₂ O ₃)	27.01	25.89	24.68	5.77
Ferric oxide (Fe ₂ O ₃)	6.25	6.59	6.50	2.02
Calcium oxide (CaO)	1.72	1.53	1.41	61.86
Sulphur trioxide (SO ₃)	-	-	-	-
Magnesium oxide (MgO)	1.88	1.91	1.82	1.86
Potassium oxide (K ₂ O)	4.49	4.20	4.06	0.36
Sodium oxide (Na ₂ O)	0.54	0.57	0.56	0.07
Titanium oxide (TiO ₂)	0.99	1.00	0.97	0.17
Loss on ignition	4.70	7.00	11.70	0.90

TABLE 2--PHYSICAL PROPERTIES OF THE FLY ASHES AND THE OPC

Physical properties	Fly ash			OPC
	FA 5% C	FA 7% C	FA 12% C	
Blaine spec. area (cm ² /g)	1680	2055	2280	3000
> 45 μm (%) *	47.60	37.10	33.60	-
> 50 μm (%) **	37.00	28.40	22.60	-
Specific gravity	2.14	2.12	2.10	3.12

* Calculated from the laser granulometry curve

** Obtained from the sieve analysis

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TABLE 3--MIXTURE CHARACTERISTICS

Mixture	Binder kg/m ³	Water kg/m ³	Sand kg/m ³	Coarse aggregate kg/m ³
Mortar	510	255	1525	-
Concrete	350	175	765	1075

TABLE 4--SLUMP OF THE DIFFERENT CONCRETE MIXTURES

Mixture		Slump (cm)
Fly ash (%)	Carbon (%)	
15	5	5
	7	6
	12	5
30	5	5
	7	5
	12	5
OPC		7

TABLE 5--FLEXURAL STRENGTH OF MORTARS (MPa)

Mixture		Time (days)			
		2	7	28	90
OPC		5.5	8.8	9.3	9.8
Blended cements		4.8	7.9	9.4	9.5
Fly ash (%)	Carbon (%)				
15	5				
	7	5.0	7.8	9.6	9.0
	12	4.6	7.3	9.3	9.1
30	5	3.1	5.5	8.3	8.1
	7	3.5	6.5	8.4	9.1
	12	3.5	5.9	8.6	9.2

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TABLE 6--COMPRESSIVE STRENGTH OF MORTARS (MPa)

Mixture		Time (days)			
		2	7	28	90
OPC		25.5	49.7	65.2	70.4
Blended cements					
Fly ash (%)	Carbon (%)				
15	5	21.9	39.8	56.5	68.8
	7	21.2	40.5	59.9	65.5
	12	20.8	40.9	57.9	71.2
30	5	13.2	27.6	42.6	53.7
	7	13.9	30.5	46.2	58.1
	12	13.7	28.7	46.4	61.7

TABLE 7--COMPRESSIVE STRENGTH OF CONCRETES (MPa)

Mixture		Time (days)			
		2	7	28	90
OPC		14.9	31.7	32.8	45.2
Blended cements		9.6	20.9	34.2	44.0
Fly ash (%)	Carbon (%)				
15	5				
	7	9.7	-	31.7	45.3
	12	11.9	24.6	33.6	43.9
30	5	9.4	19.5	28.4	33.6
	7	9.6	19.6	31.6	42.8
	12	10.4	21.2	23.4	38.5

TABLE 8--MERCURY INTRUSION POROSIMETRY DATA

Mixture		Mortars (28 days)			
		Total porosity (mm ³ /g)	Specific gravity (g/cm ³)	Specific area (m ² /g)	Total pore vol. (%)
OPC		44.70	2.17	5.40	9.70
Blended cements					
Fly ash (%)	Carbon (%)				
30	5	59.80	2.09	7.80	12.50
	7	55.80	2.09	8.10	11.60
	12	52.30	2.07	7.70	10.80

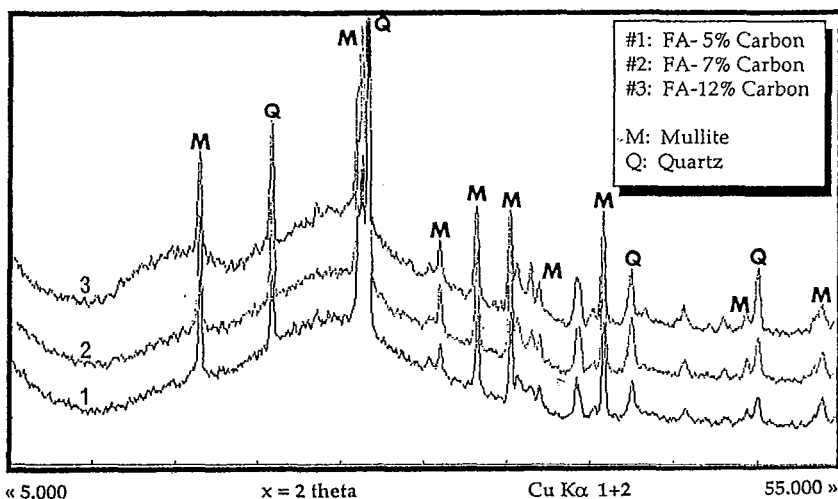


Fig. 1--Mineralogical compositions of the fly ashes



Fig. 2--SEM micrograph: Massive carbon particle

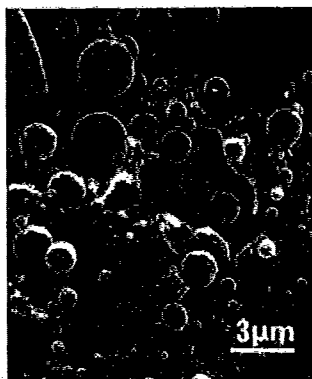


Fig. 3--SEM micrograph: Porous carbon particle surrounding microspheres

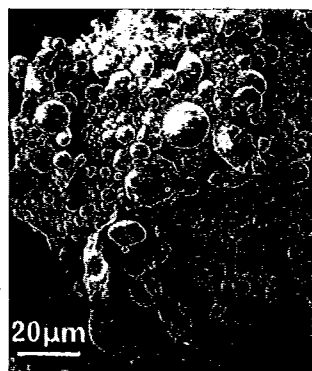


Fig. 4--SEM micrograph: Cluster of microspheres

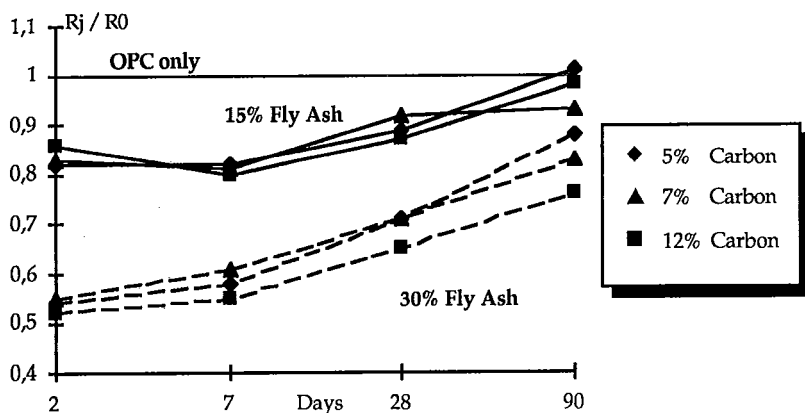


Fig. 5--Mortar strength development

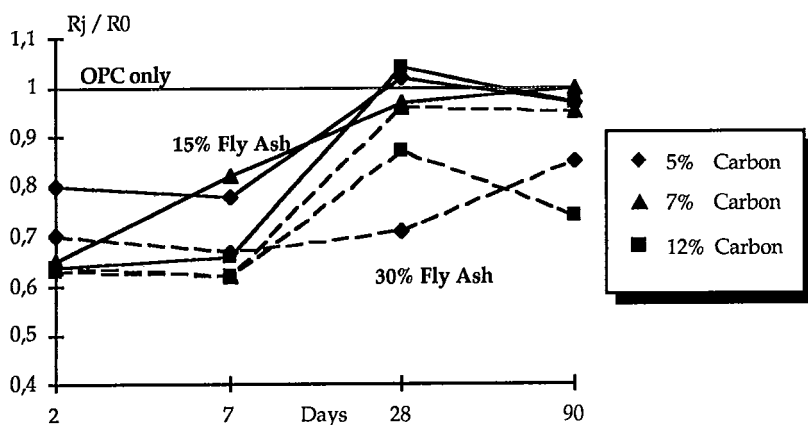


Fig. 6--Concrete strength development

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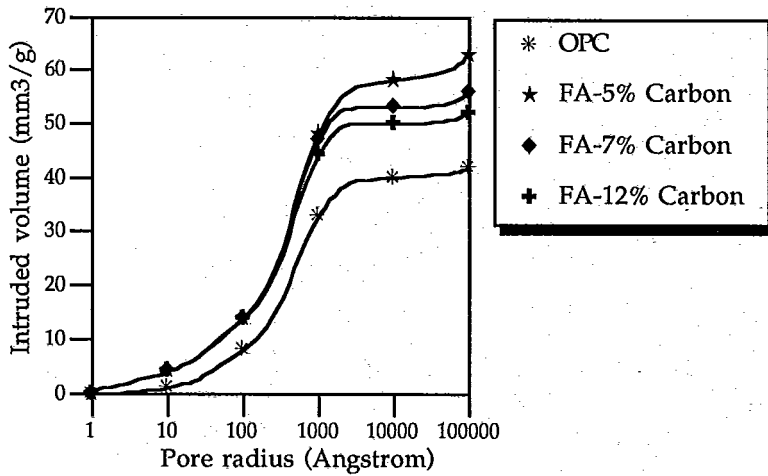


Fig. 7--Pore size distribution of mortars (28 days)

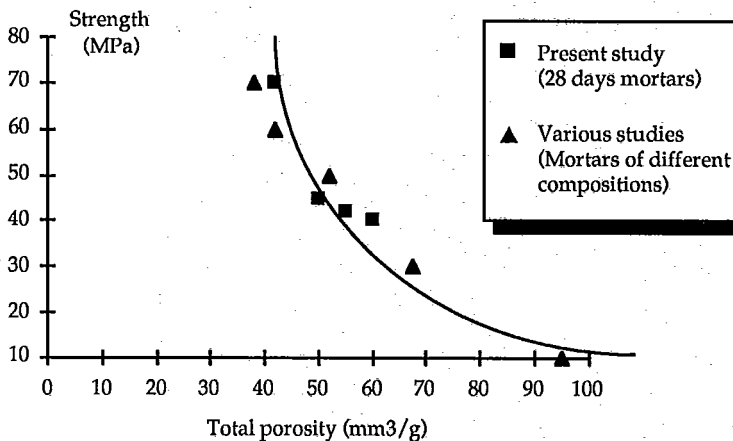


Fig. 8--Relationship between total porosity and strength of different mortar mixtures

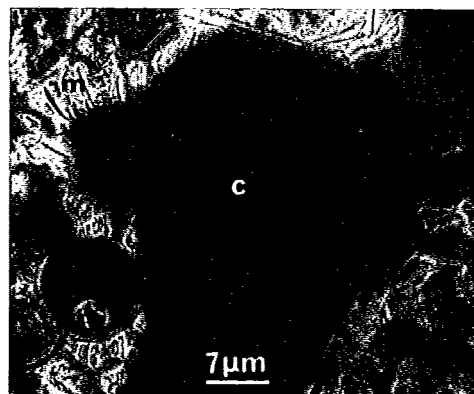


Fig. 9--SEM micrograph (polished section): Monosulfo-aluminates (M) in contact with a carbon particle (C)



Fig. 10--SEM micrograph (fractured section): Reactive fly ash (FA) and a carbon particle (C)

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Properties of High Strength Concrete Using "Classified Fly Ash"

by K. Ukita, M. Ishii, K. Yamamoto,
K. Azuma, and K. Kohno

Synopsis: The paper is concerned with the research of the effective utilization of fly ash produced from power plants. Three classes of "classified fly ash" produced by classifying conventional fly ash by air separation with the maximum particle diameters of about 20 μ m, 10 μ m and 5 μ m, have been investigated.

Special attention has been given to concrete strength enhancement effect due to classified fly ash. Experimental studies have reported on the basic properties of fresh concrete and hardened concrete having low water-binder ratio and high strength, produced by mixing the classified fly ash having the maximum particle diameter of about 10 μ m, alone or in combination with ground granulated blast furnace slag.

It is shown that the classified fly ash is an effective material that contributes to the reduction of superplasticizer requirements that is generally used in high strength concrete, improvement of workability by reduced viscosity, and improvement of strength development, whether the classified fly ash is used alone or in combination with ground granulated blast furnace slag.

Keywords: Blast furnace slag; compressive strength; fly ash; high strength concretes; modulus of elasticity; porosity; splitting tensile strength; superplasticizer; workability

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INTRODUCTION

In recent years, the demand for high quality concrete is high, and technology development activities, designed for production of high performance concrete by utilizing various admixtures and new construction methods are being pursued with vigor.

When the research achievements among these developments are considered in relation to the development of materials for high strength concrete, the use of superplasticizer or high performance water-reducing admixture is found indispensable, and that use of fine particle admixtures such as silica fume is desirable from the point of view of durability(1,2,3). While research on silica fume and ground granulated blast furnace slag is dominant, the research activities related to fly ash are relatively little, except for the use of accelerated curing such as autoclaving(4).

The authors are engaged in research involving high added value utilization of fly ash produced by thermal power plants, and have been studying their utilization in various applications; In particular, the utilization as concrete admixture, of three classes of "classified fly ash", classified by air separation method to have the maximum particle diameters of about 20 μ m, 10 μ m and 5 μ m respectively, is being investigated. In this research, it has been shown that the use of classified fly ash can reduce water requirement, improve workability, enhance strength and water-tightness, and increase resistance to alkali silica reaction in the concrete(5,6).

In this research, attention is given to the effect of classified fly ash on concrete strength, and experimental studies are reported on the basic properties of fresh and hardened samples of high strength concrete containing classified fly ash with maximum diameter of about $10\mu\text{m}$ with or without ground granulated blast furnace slag.

EXPERIMENTAL DETAILS

Materials used

Cement

Ordinary portland cement was used. Physical properties and major chemical compositions are given in Table 1.

Fly ash

The fly ash used was classified fly ash having maximum particle diameter of about $10\mu\text{m}$. Physical properties and chemical compositions are given in Table 2. In the remaining part of this paper, this classified fly ash is referred to as FA10.

Ground granulated blast furnace slag

Ground granulated blast furnace slag used had a little larger specific surface area than the conventional ones. Physical properties and chemical compositions are given in Table 3. This is referred to BS in the paper.

Aggregate

Fine aggregate used was river sand. Coarse aggregate was hard, crushed sand stone having maximum size of 20mm. Physical properties of aggregates are given in Table 4.

Admixture

A superplasticizer with the main ingredient of the anion type special activator was used. This superplasticizer was selected from three others having different main ingredients because of its very low viscosity at the same slump in a preliminary test. Also, an air-entraining agent having the main ingredient of wood-resin was used to control the air content.

Concrete mixtures

The following three series of tests were conducted in order to identify the characteristics of concrete with fly ash FA10.

Series I: General characteristics of concrete using FA10 with low water-binder ratio.

Series II: Effect of unit water content on the compressive strength.

Series III: Concrete strength based on constant binder and superplasticizer contents, that is, for the same material cost.

Concrete mixtures for these three series are shown in Table 5.

Tests and test methods

Details of tests and test methods are given in Table 6.