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

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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 lead 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

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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 asses 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 strength[1] 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_ws 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 m^3 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 m^3.
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 m^3.

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 m^3.

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/m^3 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/m^3 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/m^3 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/m^3. 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/m^3 for 52.5/20 concrete and to 290 kg/m^3 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(±) 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