Concrete containing fly ash

A brief description of the physical and chemical properties of fly ash was presented in Chapter 2. We shall now consider the use of fly ash in concrete and discuss the properties of the resulting concrete; a further discussion of the properties of the fly ash itself, in so far as they affect the properties of concrete, will also be included.

The importance of fly ash cannot be exaggerated: it is no longer a cheap substitute for cement, nor an 'extender' or an addition to the mix. Fly ash bestows important advantages upon concrete, and it is, therefore, essential to understand the role and influence of fly ash.

The variability of the properties of fly ash was mentioned in the preceding section. This variability arises from the fact that fly ash is not a specially manufactured product and cannot, therefore, be governed by strict requirements of a standard. The main influences are the nature of the coal and the manner of its pulverization, the operation of the furnace, the process of precipitation of ash from the combustion gases, and especially the extent of classification of the particles in the exhaust system. Even when all these are constant, a power station which varies its operation in response to the power demand produces a variable fly ash; this is not so with a base-load power station. The variations in the fly ash are those in glass content, carbon content, particle shape and size distribution, as well as in the presence of magnesia and other minerals, and even in colour. It is possible to improve the size distribution of fly ash particles by classification and by grinding.

As just mentioned, the burning process of pulverized coal influences the shape of the fly ash particles. High temperature favours the formation of spherical particles, but the need to reduce the emission of NO_x gases requires the use of lower peak burning temperatures so that the minerals with a high melting point do not always fuse completely. A consequence of this is a reduction in the proportion of spherical particles of fly ash and also in the proportion of particles smaller than 10 μm; however, the proportion of particles larger than 45 μm is not affected.[13.12,13.34] These changes militate against the beneficial effects of fly ash in concrete. Thus, there is need for changes in technology which will satisfy both the NO_x emission requirements and the particle properties desirable from the standpoint of their use in concrete.

It should be pointed out, however, that, in most countries, much uniform and excellent fly ash for use in concrete is consistently produced, and there is no doubt that, world-wide, the consumption of fly ash in concrete increases and is expected to continue to do so. What is not possible is to provide information about a 'standard', or even typical, fly ash. Consequently, specific guidance on the use of fly ash as a generic material cannot be presented.

Influence of fly ash on properties of fresh concrete

The main influence is that on water demand and on workability. For a constant workability, the reduction in the water demand of concrete due to fly ash is usually between 5 and 15 per cent by comparison with a Portland-cement-only mix having the same cementitious material content; the reduction is larger at higher water/cement ratios.[13.12]

A concrete mix containing fly ash is cohesive and has a reduced bleeding capacity. The mix can be suitable for pumping and for slipforming; finishing operations of fly ash concrete are made easier.

The influence of fly ash on the properties of fresh concrete is linked to the shape of the fly ash particles. Most of these are spherical and solid, but some of the large particles are hollow spheres, known as cenospheres, or are vesicular and irregular in shape.

The reduction in water demand of concrete caused by the presence of fly ash is usually ascribed to their spherical shape, this being called a 'ball-bearing effect'. However, other mechanisms are also involved and may well be dominant. In particular, in consequence of electrical charges, the finer fly ash particles become adsorbed on the surface of the cement particles. If enough fine fly ash particles are present to cover the surface of the cement particles, which thus become deflocculated, the water demand for a given workability is reduced.[13.156] An amount of fly ash in excess of that required to cover the surface of the cement particles would confer no further benefit with respect to water demand. Indeed, the reduction in water demand becomes larger with an increase in the fly ash content only up to about 20 per cent.[13.156] The effect of fly ash is not additional to the action of superplasticizers. Thus, it seems likely that the action of fly ash, like that of superplasticizers, on water demand is through dispersion and adsorption of the fly ash on the particles of Portland cement.[13.156]

The presence of carbon in fly ash was referred to on p. 85. One consequence of a high carbon content in fly ash is that it adversely affects workability. Variation in carbon content may also lead to erratic behaviour with respect to air entrainment, some air-entraining agents becoming adsorbed by the porous carbon particles.

Fly ash in the mix has a retarding effect, typically of about 1 hour, probably caused by the release of SO_4^{--} present at the surface of the fly ash particles. The retardation may be advantageous when concreting in hot weather; otherwise, an accelerator may be needed. Only initial setting is delayed, the time interval between setting and final stiffening being unaffected.

Hydration of fly ash

Pozzolanic reactions were considered in Chapter 2. In the case of fly ash, the products of reaction closely resemble *C-S-H* produced by hydration of Portland cement. However, the reaction does not start until sometime after mixing. In the case of Class F fly ash (see p. 85), this can be as long as one week or even more. An explanation of this delay, offered by Fraay *et al.*[13.15] is as follows. The glass material in fly ash is broken down only when the pH value of the pore water is at least about 13.2, and the increase in the alkalinity of the pore water requires that a certain amount of hydration of the Portland cement in the mix has taken place. Moreover, the reaction products of Portland cement precipitate on the surface of the fly ash particles, which act as nuclei.

When the pH of the pore water becomes high enough, the products of reaction of the fly ash are formed on the fly ash particles and in their vicinity. A consequence of these early reactions is that their products often remain in the shape of the original spheres of fly ash. With the passage of time, further products diffuse away and precipitate within the capillary pore system; this results in a reduction in the capillary porosity and, consequently, a finer pore structure (see Fig. 13.1).[13.15]

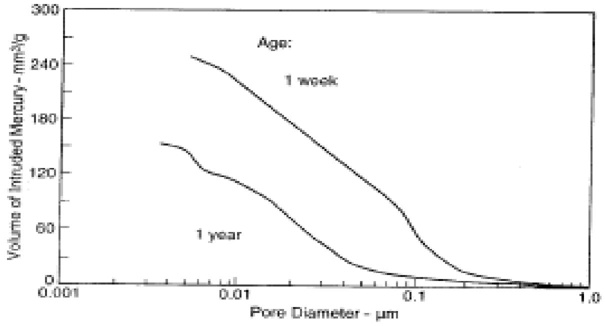

Fig. 13.1 Change in pore size distribution (determined by mercury porosimetry) in cement paste containing 30 per cent of Class F fly ash by mass of total cementitious material (based on ref. 13.15)

The sensitivity of the fly ash reaction to the alkalinity of the pore water means that the reactivity of fly ash is influenced by the alkali content of the Portland cement with which the fly ash is to be used. (This is, however, disproved by Osbaeck.[13.114]) For example, because rapid-hardening Portland (Type III) cement leads to a more rapid development of alkalinity of pore water than ordinary Portland cement, the pozzolanic reaction of fly ash starts earlier when Type III cement is used. The preceding observations illustrate the complexity of the behaviour of fly ashes which makes generalizations difficult and points to the need for tests involving both the fly ash and the Portland cement which are to be used together.

A consequence of the delay in the reactions of fly ash is the beneficial pattern of heat evolution by hydration (see Chapter 8).

Further progress of the pozzolanic reaction of Class F fly ash is slow: the presence of as much as 50 per cent of unreacted fly ash after one year is quoted by Fraay *et al.*[13.15]

Whereas Portland-cement-only concrete with a medium or a high water/cement ratio, under suitable storage conditions, continues to gain strength over a long period, this is not so when fly ash is incorporated in the mix. No further strength development beyond the age of 3 to 5 years was found in concretes with water/cement ratios of 0.5 to 0.8; the Class F fly ash content, expressed as a percentage of the mass of the total cementitious material, ranged from 47 to 67.[13.16,13.17]

Class C fly ash (see p. 85) which has a high lime content, reacts, to some extent, direct with water; in particular, some C_2S may be present in the fly ash[13.157] and this compound reacts to form C-S-H. Also, crystalline C_3A and other aluminates are reactive.[13.9] In addition, as with Class F fly ash, there is a reaction of silica with calcium hydroxide produced by the hydration of Portland cement. Thus, Class C fly ash reacts earlier than Class F fly ash, but some Class C fly ashes do not show a long-term increase in strength.[13.18]

Because the reactions of fly ash in concrete take a long time, prolonged wet curing is essential. A consequence of this is that tests on compression specimens cured under standard wet conditions may be misleading with respect to the strength of concrete in situ. This, of course, is also the case with Portland-cement-only concrete, but the influence of curing on strength is more pronounced when fly ash is included in the mix.

Higher temperature, between 20 and 80 °C (68 and 176 °F) accelerates the reactions of fly ash to a greater extent than is the case with Portland cement alone. However, the usual retrogression of strength follows (cf. p. 359).[13.21] The reduction in strength with an increase in temperature between 200 and 800 °C is also similar to, or possibly even greater than, that in concrete made with Portland cement only.[13.20]

Because the reactivity of fly ash sharply increases with an increase in temperature, the behaviour of concrete containing fly ash may be different in massive sections (where hydration of the Portland cement component raises the temperature) from the behaviour in small concrete elements at room temperature.[13.9] This observation is relevant to any prediction of the rate of gain of strength of concrete containing fly ash.

Strength development of fly ash concrete

The test method of ASTM C 311-94a provides for the measurement of strength of mortars containing fly ash representing 20 per cent by mass of the total cementitious material and establishes a strength activity index. However, as already discussed, the reactions of fly ash are affected by the properties of Portland cement with which it is used. Moreover, in addition to the effect of chemical reactions, fly ash has a physical effect of improving the microstructure of the hydrated cement paste. The main physical action is that of packing of the fly ash particles at the interface of coarse aggregate particles, which are absent in the mortar used in the test of ASTM C 311-94a.[13.12]

For these reasons, strength activity measurements do not adequately establish the contribution of fly ash to the development of strength of a particular *concrete* in which the fly ash is to be incorporated. This is an example of the inappropriateness of tests on mortar for the purpose of establishing the effect of a given factor on concrete.

The extent of packing depends both on the fly ash and on the cement used: better packing is achieved with coarser Portland cement and with finer fly ash.[13.12] One beneficial effect of packing on strength is a reduction in the volume of entrapped air in the concrete,[13.12] but the main contribution of packing lies in a reduction in the volume of large capillary pores.

It is worth noting that the positive influence of the fineness of fly ash is coupled with its spherical shape. Therefore, grinding of fly ash, although it increases fineness, may result in the destruction of spherical particles, with a consequent increase in water demand of the mix due to the irregular angular shape of the fly ash particles.[13.26]

Control of particle size of fly ash is usually effected on the basis of residue larger than 45 μm (No. 325 ASTM) sieve, but this is not sufficiently discriminatory with respect to the reactivity of fly ash and its contribution to strength development in concrete.

Typically, about one-half of the particles in fly ash are smaller than 10 μm, but there may be wide variations. It is particles of that size that are most reactive.[13.22] The reactivity is very high when the median diameter of fly ash particles is smaller still: 5 or even 2.5 μm.

As far as the coarse particles of fly ash are concerned, Idorn and Thaulow[13.23] suggested that these particles can be considered as 'microaggregate' which improves the density of the hydrated cement paste in a manner similar to the effect of unhydrated remnants of Portland cement particles. This is beneficial with respect to strength, resistance to crack propagation, and stiffness. The resulting system of capillary pores is better able to retain water which can be available for long-term hydration.[13.23]

The glass content of the fly ash strongly affects its reactivity. In the case of Class C fly ash, the lime content is also a factor influencing reactivity. However, knowledge of these characteristics does not make it possible to predict the performance of any given fly ash, and tests are necessary; tests with the actual Portland cement to be used are preferable.

It was mentioned on p. 654 that the beneficial influence of fly ash upon water demand does not extend beyond a fly ash content of 20 per cent by mass. An

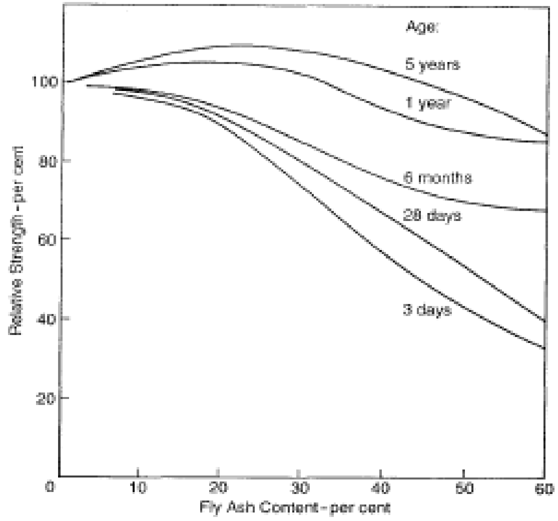

Fig. 13.2 Influence of content of fly ash in the cementitious material (by mass) on strength of hardened cement paste[13.19]

excessive content of fly ash is not beneficial from the point of view of strength development either. The limiting content is probably around 30 per cent by mass of total cementitious material, as can be seen from Fig. 13.2.[13.19]

As has been repeatedly stated, quantified predictions of the influence of fly ash on strength are not possible. For example, the data of Fig. 13.2 can be contrasted with the apparent lack of a positive influence of fly ash upon strength even as late as one year, which was reported by the Portland Cement Association.[13.14]

Average values of strength of concrete cylinders moist cured at 23 °C (73 °F) (obtained from tests on six Class F fly ashes and four Class C fly ashes) are shown in Table 13.1.[13.14] All the mixes had a total cementitious material content of 307 kg/m^3 (517 lb/yd^3) with a 25 per cent content of fly ash by mass of total cementitious material. The water/cement ratio was 0.40 to 0.45, and the mixes had a slump of 75 mm. The same table gives the strength of a Portland-cement-only concrete with the same cement content and the same water/cement ratio. It is worth adding that the maximum size of aggregate was 9.5 mm ($\frac{3}{8}$ in.) so that the beneficial effect of fly ash with respect to packing around the coarse aggregate particles was smaller than would be the case with conventional concrete; therein may lie the explanation of the apparently limited effect of fly ash on strength.

In this connection, it should be noted that, because the specific gravity of fly

Table 13.1 Typical Compressive Strength of Fly Ash Concretes[13.14]

Cementitious material	*Compressive strength, MPa (psi) at age (days):*						
	1	*3*	*7*	*14*	*28*	*91*	*365*
Portland cement	12.1 (1750)	21.2 (3070)	28.6 (4150)	33.9 (4910)	40.1 (5810)	46.0 (6670)	51.2 (7420)
Class F fly ash (25%)	7.1 (1030)	13.9 (2010)	19.4 (2820)	24.3 (3520)	30.3 (4400)	39.8 (5770)	47.3 (6860)
Class C fly ash (25%)	8.9 (1290)	19.0 (2760)	24.1 (3490)	28.5 (4140)	29.4 (4260)	40.5 (5880)	45.6 (6620)

ash is much lower than that of Portland cement (typically 2.35 as compared with 3.15), for the same mass, the volume of fly ash is about 30 per cent higher than that of cement. This must be taken into account in determining the mix proportions of concrete: usually, a lower content of fine aggregate is used than with Portland-cement-only concrete.

As for physical properties of concrete other than strength, it appears that creep and shrinkage are not fundamentally affected by the use of fly ash.

Durability of fly ash concrete

As discussed in Chapters 10 and 11, the selection of ingredients of a concrete mix must include consideration of their effect on durability. As in the case of strength, much depends on the actual fly ash used.

One consequence of the slow reaction of fly ash in the concrete is that, initially, the concrete has a higher permeability than concrete with a similar water/cement ratio (on the basis of the total cementitious material) but containing Portland cement only. However, with time, fly ash concrete acquires a very low permeability.[13.15] It is, nevertheless, essential that the concrete containing fly ash undergoes prolonged curing. The detrimental effect of inadequate curing on the absorption properties of the outer zone of concrete is greater the higher the fly ash content.[13.101] This effect is even more pronounced than the effect on the strength of concrete containing fly ash. Thus, reliance on strength alone may not be adequate for the purpose of assessing the durability of fly ash concrete in cases where penetration of concrete by aggressive agents is critical.

With respect to the resistance to sulfate attack, it should be noted that alumina and lime in the fly ash may contribute to the sulfate reactions. Specifically, when present in the glass part of the fly ash, alumina and lime provide a long-term source of material which can react with sulfates to form expansive ettringite.[13.25] A high silica/alumina ratio probably reduces the vulnerability to sulfate attack[13.28] but no reliable generalization is possible.

It seems that inclusion of Class F fly ash in concrete improves its sulfate resistance, probably mainly through the removal of calcium hydroxide. The content of fly ash should generally be between 25 and 40 per cent of the total cementitious material. Reliable information on the behaviour of Class C fly ash is not available. Indeed, the role of Class C fly ash with respect to sulfate resistance is not clear.[13.18]

Tests on air-entrained concrete with a water/cement ratio of 0.33 and a Class F fly ash content of 58 per cent by mass of cementitious material have shown an excellent resistance to freezing and thawing.[13.30] It should be noted that, for concrete exposed to de-icing agents, ACI 318-02[13.116] limits the mass content of fly ash and other pozzolanas to 25 per concerned, in quantities up to 20 per cent of the total mass of cementitious material, this fly ash has no adverse effect on the resistance to freezing and thawing of air-entrained concrete. At high contents of Class C fly ash, the resistance was found to be impaired, possibly due to an increase in the porosity of the hardened cement paste caused by the movement of fibrous ettringite into the air voids.[13.1]

With respect to air entrainment of fly ash concrete, the problems caused by carbon, discussed on p. 551, should be borne in mind.

Bilodeau *et al.*[13.124] found that fly ash, both Class F and Class C, at least when present in large proportions, results in concrete with a poor resistance to de-icing agents, even though the concrete has a good resistance to freezing and thawing. The reasons for this have not been established.

Because of the reduced permeability of mature concrete containing fly ash, the chloride ingress into such concrete is reduced. Even when the content of Class F fly ash is as high as 60 per cent by mass of cementitious material, the passivation of steel embedded in mortar and the risk of corrosion were found to be unimpaired.[13.24] This was confirmed by other tests on concretes with high fly ash contents (58 per cent of the total cementitious material) and water/cement ratios between 0.27 and 0.39, which have shown a very good resistance to chloride penetration.[13.24]

Nevertheless, in some countries[13.12] the use of fly ash in prestressed concrete is not permitted, it being thought that carbon in the fly ash may contribute to stress corrosion of the prestressing steel.

The abrasion resistance of concrete containing fly ash, Class F or Class C, is unimpaired[13.29] or possibly even improved.[13.31]

Fly ash, in adequate quantity in the mix, is beneficial in reducing the alkali–silica reaction (see p. 520) but the mechanisms involved are complex and imperfectly understood. The beneficial effects may arise from the denser structure of the hydrated cement paste which impedes the movement of ions, or from the preferential reaction of the alkalis with the fly ash so that they are not available for reaction with the silica in the aggregate.[13.28] It should be pointed out that fly ash itself contains alkalis, but typically only about one-sixth of the total alkali content in the fly ash is water-soluble, and therefore potentially reactive, the remainder being combined. Whether or not the fly ash contributes alkalis to the pore water in concrete seems to depend on the alkalinity of the cement used.[13.27]

There is no beneficial effect of fly ash with respect to the alkali–carbonate reaction.