The effect of fly ash properties on concrete strength

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Fly ash or pulverised fuel ash is a by-product of the combustion of pulverised coal in thermal power plants. The recognition that fly ash frequently exhibits pozzolanic properties has led to its use as a constituent of concrete. In South Africa the carbon content (as measured by loss on ignition, LOI) and the particle size of classified ash is limited to 5 % LOI and less than 12,5 % larger than 45 µm respectively. Furthermore, the maximum percentage of cement that can be replaced using ash is normally limited to 30 %. A literature review was undertaken to establish the relevance of these limitations based on international research findings. In this article results published by other researchers were reworked and are presented in graphical form to emphasise the effect of carbon content and particle size. Research results indicate that ash with high carbon content reduces the workability of mixtures, thus increasing the water demand and thereby reducing the strength of the concrete. No proof could be found that the particle size of ash has an effect on the strength of the concrete. The use of large percentages of ash replacement does result in reduced early strength, but for specific applications there could be benefits in replacing high percentages of cement with ash. Research should be conducted to establish whether sources of ash previously deemed unfit for use in concrete could be used in future.

INTRODUCTION

Fly ash (fa) or pulverised fuel ash is a by-product of the combustion of pulverised coal in thermal power plants. Mechanical collectors or electrostatic precipitators remove it as a fine particulate residue from the combustion gases. The fineness of the pulverised coal and the type of dust collection equipment used largely determine the range of particle sizes in any given fly ash. The fly ash collected from boilers where mechanical collectors alone are employed is coarser than fly ash from plants using electrostatic precipitators. The types and relative amounts of mineral matter in the coal used determine the chemical composition of fly ash.

The recognition that fly ash frequently exhibits pozzolanic properties has led to its use as a constituent of concrete. According to Smith (1967) a pozzolan can be defined as 'a finely divided siliceous material which reacts with lime in the presence of water to give cementitious products'. The cementing action of the pozzolan is believed to be dependent upon the reaction between it and lime hydrate liberated from the cement during hydration.

Fly ash can be divided into two types that differ from each other mainly in terms of the calcium content. Low-calcium fly ash (ASTM class F) contains less than about 10 % CaO and it is generally a product of combustion of anthracite and bituminous coals. The principal crystalline materials in low-calcium fly ash are quartz, mullite and hematite or magnetite. As these materials are non-reactive at ordinary temperatures, their presence in large quantities tends to reduce the reactivity of fly ash. High-calcium fly ash (ASTM class C) is in general more reactive as it contains more calcium in the form of reactive crystalline compounds.

Fly ash is normally used in concrete for economic and durability considerations as a partial replacement for Portland cement. In the amounts normally used, most low-calcium fly ashes tend to reduce the early strengths up to 28 days, but improve the ultimate strength (after more than a year). When fly ash is used as a partial replacement for fine aggregates, the strength at both early and later ages can be significantly improved. The strength gain at early ages is in part due to the slight acceleration in Portland cement hydration, while the strength gain at later ages is mostly as a result of pozzolanic reaction, causing pore refinement and replacing the calcium hydroxide that does not have any cementitious properties with calcium silicate hydrate, which is a binder. In South Africa fly ash should comply with the requirements of the South African standard specification for Portland cement extenders (SABS 1491: Part II - 1989). Fly ash complying with SABS 1491: Part II may be used as a cement extender with Portland cement for use in concrete. These blended cements should comply with SABS EN 197.

SABS EN 197-1 (2000) states that 'siliceous fly ash (class V) is a fine powder of mainly spherical particles having pozzolanic properties'. The fly ash should consist essentially of reactive SiO_2 and Al_2O_3, with the remainder containing Fe_2O_3 and other oxides. The proportion of reactive CaO is limited to less than 10 % per mass, while the reactive SiO_2 content shall not be less than 25 % per mass. Both SABS 1491: Part II and SABS EN 197-1 (2000) limit the loss on igni-

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tion of fly ash to 5 % per mass. In order to comply with SABS 1491: Part II - 1989 not more than 12,5 % of the particles in a fly ash should be retained on a sieve with square apertures with a nominal size of 45 µm, the water requirement should be no more than 95 % (by mass) of the control, and the compressive strength obtained from the pozzolanic reactivity test should not be less than 5 MPa. Pozzolanic activity is defined as the ability of the material to develop strength when it reacts with lime under moist conditions. The reactivity of lime with Portland cement extenders is determined according to SABS Method 1153 - 1989, where the lime and sand content of the mixture is fixed and the mass of extender added is calculated to be twice the volume of the lime, while the water content is adjusted to maintain constant workability. In general practice Portland cement with up to 30 % fly ash is considered suitable for durable concrete (SABS 0100–2:1992).

BACKGROUND

The National Building Research Institute (NBRI) of the CSIR did the first investigation into the use of South African fly ash as cement extender in 1955 and research into fly ash and its use is still ongoing. According to Barker (1981) 'attempts to evaluate the performance of South African fly ashes in blended cements showed poor correlation between the commonly used ash quality criteria of loss on ignition and fineness as related to performance in concrete'. In an overview of their research on fly ash the CSIR concluded that there is a correlation between the residue on the 45-mm sieve and the pozzolanic activity index. This conclusion is used to justify the use of this limit in specifications. However, in the same overview it is stated that the pozzolanic activity indices do not always reflect the strength that develops in a concrete containing blended cements.

Currently there is an international trend to reduce the environmental impact of manufacturing concrete by increasing the use of waste materials in concrete. Fly ash that comply with SABS 1491 is produced at only three South African power stations (Matla, Lethabo and Kendal) while large volumes of ash produced are still placed in landfill (Krüger 1999). Although the ash from other sources might not be of the same quality than the ash currently used in concrete, it may still be advantageous to use these ashes as cement extenders in concrete. Waste materials can however only be used in concrete if they are not detrimental to the short- or the long-term properties of the concrete. To establish the possible effect of fly ash properties on concrete strength and durability an extensive literature review was conducted. This article contains a summary of research results highlighting the effect of fly ash properties on the strength of concrete.

HYDRATION AND MICROSTRUCTURE

The chemical composition and reactivity of fly ashes vary with the mineralogy of impurities in the coal. All commercial fly ashes react with lime hydrate in the presence of water to produce highly cementitious products that are insoluble in water. Berry *et al* (1994) investigated the hydration mechanism of high-volume fly ash concrete binders using mixtures containing superplasticisers with a water-cementitious ratio of 0,3 and cement replacement of 58 % per mass by fly ash. They concluded that these pastes appear to hydrate and gain strength by the interaction of at least three of the following mechanisms:

- hydration of Portland cement by normal chemical reaction, slightly accelerated at early ages
- improved densification through particle packing, aided by the use of superplasticisers and the spherical form of fly ash
- reaction of fly ash particles that produce insoluble silicate and aluminate hydrates at particle boundary regions at late ages
- hydration of individual fly ash particles that remain physically intact and largely unchanged in morphology and thus capable of filling void space

These functions are probably common to all cement-fly ash systems, but they become more measurable and hence contribute to material properties at high levels of cement substitution.

FLY ASH SHAPE AND SIZE

Fly ash particles are mostly spherical in shape, with sizes ranging from approximately 1 to 100 µm in diameter with more than 50 % under 20 µm. The particle size distribution, morphology and surface characteristics of the fly ash have a considerable influence on the water requirement and workability of freshly made concrete and on the rate of strength development in hardened concrete.

According to Sarkar and Ghosh (1993) fly ash particles of very small size are mostly made up of clear glass spheres. Spongy particles formed either by fusion of many fine particles, or from ore mineralic particles are also common in most fly ashes. The clear glass spheres are smaller than other particles, and as a result they have higher specific areas than the spongy particles that are larger and generally have lower specific surface areas. About 60 % of the particles in the fly ash have diameters of less than 3 µm but these particles constitute less than 10 % of the total mass. The particles in bituminous ash range from less than 1 µm to over 100 µm but the average particle size in such ashes vary from approximately 7 µm to 12 µm. The surface area of fly ash particles have been reported to vary from about 2 000 cm^2/g to 10 000 cm^2/g depending on the proportion of fine particles in the fly ash.

Most fly ashes contain up to 10 % unburnt carbon and this carbon is generally present in the form of cellular particles larger than 45 µm. Large amounts of carbon in fly ash is considered harmful, as the cellular particles of carbon tend to increase the water requirement for a given consistency and the admixture requirement for entrainment of a given volume of air.

THE EFFECT OF FLY ASH ON THE STRENGTH OF CONCRETE

Davis *et al* published the results of the first extensive study on the effect of fly ash on the properties of concrete in 1937. In this study 15 American fly ashes were blended with seven cements in blends of up to 50 % fly ash (by mass of cement). These results indicated that fly ashes of moderate or low carbon content and moderately high fineness could be used as a replacement for Portland cement to produce concrete with properties equal or superior to those of concrete containing no fly ash. Some of the results obtained from this study (Davis *et al* 1937) using fly ash from Chicago are summarised in figure 1, where the compressive strength of mixtures of different ages is shown as a function of the percentage of cement replaced with fly ash. The strength is presented as a percentage of the strength obtained from a mixture with the same workability containing no fly ash. The water/cement ratio of the mixtures varied between 0,43 for the mixture containing no fly ash and 0,40 for the mixtures containing 20 % and 30 % ash. At early ages the compressive strengths (up to 28 days) of all concretes containing fly ash are lower than that of the corresponding concrete containing normal Portland cement, and the higher the proportion of ash the lower the strength. At later ages (3 months, 1 year) the trend is reversed, for up to 30 % ash all the concretes containing fly ash achieved a higher strength than the control, and the higher the fly ash content the higher the strength. The strength at 3 months of mix containing 50 % fly ash was, however, just below that of the control indicating an optimum percentage fly ash of about 30 % at this age of testing. Unfortunately the researchers did not report a one-year test for the 50 % fly ash mix, but there is no reason to suggest that the one-year results would not follow a similar trend to the three-month results but with a different optimum percentage of fly ash.

Brink and Halstead (1956) investigated 34 fly ashes from 19 different sources and they concluded that the strength

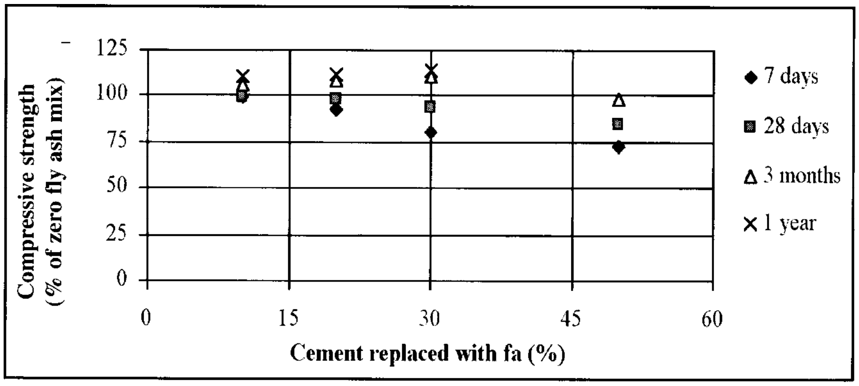

Figure 1 Effect of cement replacement on compressive strength

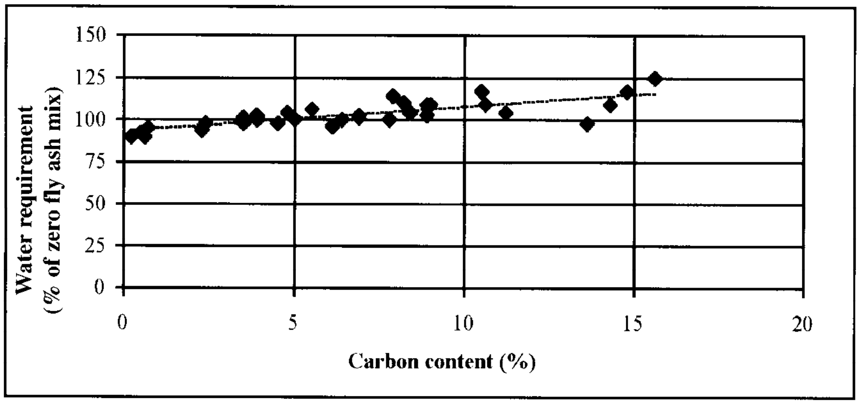

Figure 2 Effect of carbon content on water requirement

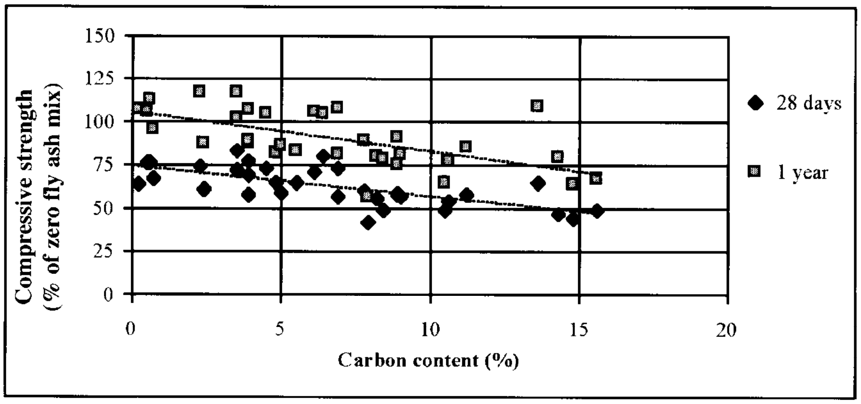

Figure 3 Effect of carbon content on compressive strength

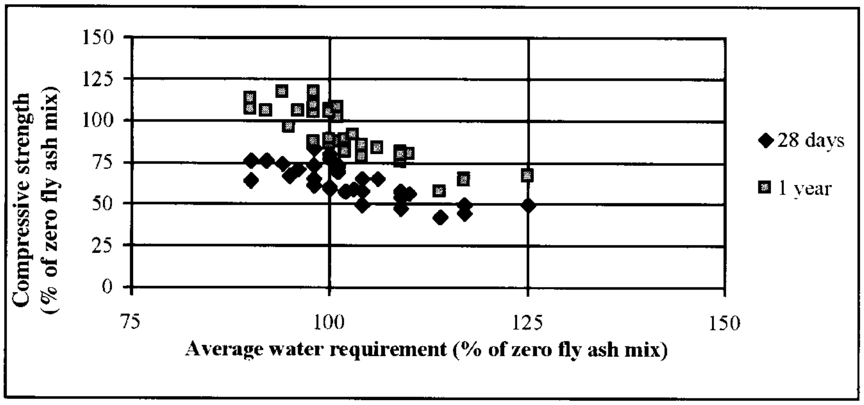

Figure 4 Effect of water requirement on compressive strength

development of Portland cement fly ash mortars is related to

- the carbon content of the fly ash
- the 45-μm sieve residue, and
- the water requirement for mortars containing fly ash

The effect of fly ash on the 28-day, three-month and one-year compressive strength of mortar was determined by replacing up to 50 % of the cement (by volume) with fly ash. The water added to each mixture was adjusted to maintain a uniform consistency.

The water requirement for the different fly ashes was considered to be a function of the carbon content of the ash; the higher the carbon content the higher the water demand, as shown in figure 2.

As would be expected, the higher carbon content also resulted in lower compressive strength, as seen in figure 3, which shows results for mixtures with constant workability containing 35 % fly ash. It can be seen from this figure that, although the 28-day compressive strength of all the mixtures containing fly ash was lower than that of the mixture without ash, the ultimate strengths (one year) of those made with low-carbon (less than 5 %) fly ash was higher than that of the control without fly ash.

Figure 4 shows these same results with the compressive strengths presented as a function of the water requirement. Again it can be seen that the 28-day strength for all mixes containing fly ash are below that of the zero fly ash mix. However, the ultimate strengths (ie one year) of the mixes in which the water requirement was similar to or lower than that of the control (ie those with a carbon content below about 5 %) were similar to or above that of the control. These results suggest that it is not the carbon content *per se* that causes the reduction in strength but it is simply due to the increased water demand required to achieve constant workability. It is likely that if water-reducing admixtures were used to maintain the workability, strengths could be achieved that were comparable with those of the control.

Figure 5 presents the relationship between compressive strength and 45-μm sieve retention and shows a reduction in strength for an increase in particle size. The ultimate strength of the mixtures containing fly ash with a 45-μm sieve retention of less than 12,5 % was higher than that of the control without fly ash. However, these results were obtained for mixtures in which the water content was varied in order to achieve a constant workability.

Figure 6 shows that there is a relationship between 45-μm sieve retention and water requirement; the coarser the fly ash the higher the water demand, but in ashes with less than 12,5 % retained on a 45-μm sieve the water demand was less than in mixtures without fly ash. This suggests that, as with carbon con-

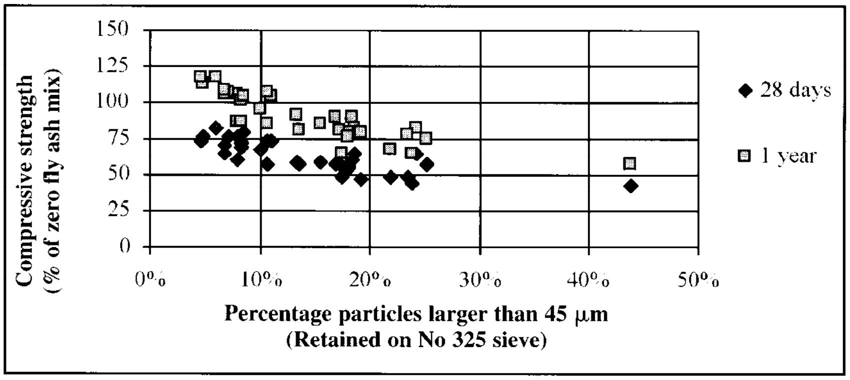

Figure 5 Effect of particle size on compressive strength

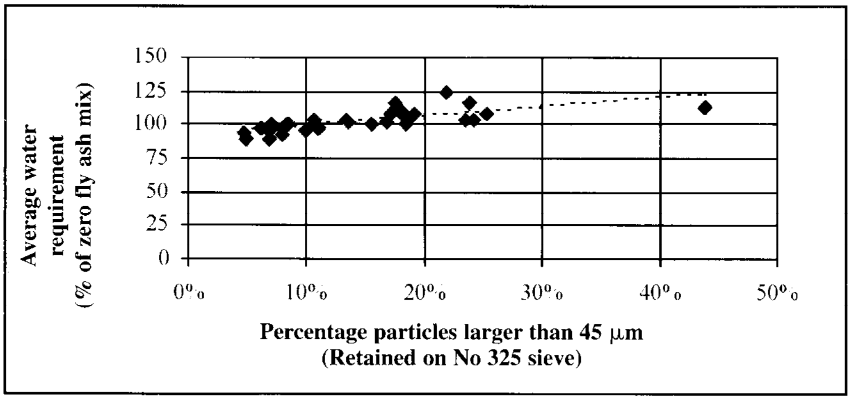

Figure 6 Effect of particle size on water requirement

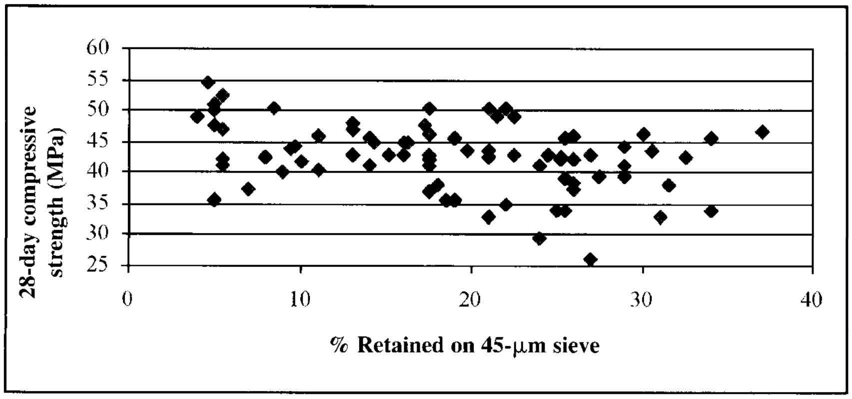

Figure 7 Compressive strength versus particles retained on 45-μm sieve

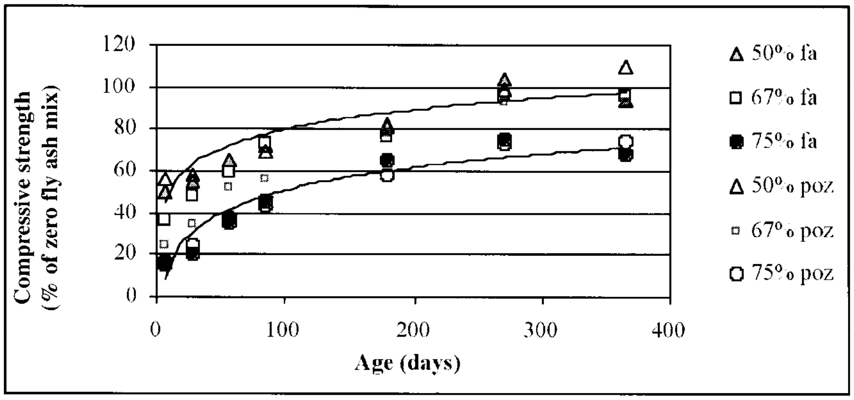

Figure 8 Strength development of cement pastes containing high volumes of fly ash

tent, it is not the coarser material *per se* that leads to a reduction in strength but the higher water demand needed to maintain constant workability. It is highly likely that the use of water-reducing admixtures to maintain workability without increasing water content would have prevented the reduction in strength observed.

Cabrera *et al* (1984) reported on the results of an extensive test programme involving almost 250 different samples of ash taken from eight different power stations in the UK. The average particle size of the ashes from the different sources, as measured by the 45-μm sieve residue test, ranged from 6 % to 30 % and the ashes from five of the eight sources failed to meet the limit of not more than 12,5 % retained. Average carbon content as measured by the loss on ignition (LOI) test ranged from 2,5 % to 5,5 %. Concrete mixes were made with 30 % (by mass) replacement of cement with fly ash and the water content of each was adjusted to give a nominal slump of 75 mm. The relationship between 28-day compressive strength and the 45-μm sieve residue is shown in figure 7, from which Cabrera concluded that 'the 45-μm sieve residue considered by so many to be an important characteristic of fly ash shows no correlation with concrete strength' and, in addition, 'other characteristics (LOI, specific surface area, pozzolanic index) also show no correlation with concrete strength'. In his discussion Cabrera highlights the disagreement that abounds between different researchers as to which test methods most accurately predict the performance of fly ash. In conclusion he states that the results from his work 'convincingly demonstrate that fly ash taken directly from power station hoppers can be successfully used in concrete production. Furthermore, the analysis of the data reveals that the rigid limits set down by current British Standards are inappropriate. The ash characteristics (45-μm sieve residue and LOI) specified therein have no relation to either the concrete strength or to the fresh concrete water demand. These tests are not even good indicators of variability of ash between power stations.'

Kearsley (1999) investigated the effect of high volumes of ash on the compressive strength of cement pastes by replacing (per mass) 50 %, 67 % and 75 % of a CEM I 42.5R cement with siliceous ash. First a classified fly ash with 8 % particles larger than 45 μm was used and then the test was repeated using an unclassified fly ash (poz) from the same source with 39 % of the particles larger than 45 μm. Unlike most of the workers referred to previously, Kearsley kept the water/binder ratio constant at 0,3 rather than varying the water content and keeping the workability constant. The compressive strength of the paste was determined on 100-μm cubes that were wrapped in plastic within 24 hours of casting and kept in a constant temperature room (± 22 °C and

60 % RH) up to the day of testing. The results are shown in figure 8, where the compressive strength of the samples containing fly ash is expressed as a percentage of the strength at the same age of the mixture containing no fly ash. From this graph it can be seen that the trends shown by the classified and unclassified fly ash are similar, indicating that, with this ash source, the particle size of the fly ash as represented by the percentage retained on the 45-µm sieve does not have a significant influence on the strength development of cement pastes containing large volumes of fly ash. Although the use of large volumes of fly ash resulted in a reduction in early-age (less than six months) strength, up to 67 % of the cement can be replaced without a significant reduction in long-term (more than nine months) strength. However, for the mixtures where 75 % of the cement was replaced, the long-term strength was reduced by more than 25 %.

In 1968 Cannon (1968) published an article on the proportioning of fly ash mixes for strength and economy discussing a method that was developed by the Tennessee Valley Authority (TVA) based on experience gained from using fly ashes over a twelve-year period in all classes of concrete. This method aims at designing the most economical mixture with a certain 28-day or 90-day strength. Based on the required strength and the cost of fly ash and cement, an optimum fly ash content (% of cement, content by mass) can be determined. The water-cement ratio that would yield the required strength in a control mix (without fly ash) can be determined and this water content can now be adjusted according to the fly ash content by using a set of graphs produced by the TVA. Cannon concluded that fly ash should be proportioned in concrete on the basis of economy and equal strength requirements and not as a straight substitution for cement either on a mass or volume basis. He argued that economy should be the only restriction placed on the proportions of fly ash to cement used. Based on TVA's experience Cannon stated that 'the addition of fly ash as an additional variable in concrete does not normally mean an increase in the coefficient of variation of the concrete, since fly ash concrete at a given plant will almost always have an equal or lower coefficient of variation for a properly designed mix than a comparable mix without fly ash'. This statement is of interest especially if one takes into account the fact that when it was made it was TVA policy to use the source of fly ash which offered the greatest economy in the concrete for each particular construction project regardless of whether or not the fly ash met Federal and ASTM specifications for fineness.

Hassan *et al* (1997) investigated the influence of fly ash content and curing temperature on the properties of high-performance concrete. They compared the properties of mixes containing ordinary Portland cement to mixes with equal workability, where 30, 50 or 70 % of the cement (by mass) had been replaced with fly ash. Equal workability was achieved by reducing the water / (opc+fa) ratio of the mix. The results of these tests not only confirmed that the water demand of a concrete mixture decreased with increased fly ash content but they also indicated that there was no unique relationship between fly ash content and strength, as the strength varied with the age of the concrete and the curing temperature. At early age (one day) the compressive strength is inversely related to the fly ash content but this linear relationship is not valid at later ages. At three days and beyond there is clearly an optimum fly ash content for maximum compressive strength. This optimum fly ash content increases from 5 % at three days to 20 % at 90 days for specimens cured at 20 °C, while the optimum increases from 15 % at three days to 30 % at 90 days for specimens cured at 45 °C. For specimens cured at 20 °C for 90 days, equal strength to the opc mix was obtained for mixes with between 30 % and 40 % cement replacement, while for concrete cured at 45 °C equal strength to the opc mix was achieved at three days with a fly ash content of up to 30 % and at 90 days with a fly ash content up to 60 %.

CONCLUSIONS

From the literature reviewed on the influence of the properties of fly ash on concrete strength the following conclusions can be drawn:

- The water demand for constant workability appears to be related to the carbon content of the ash. Higher carbon contents result in higher water demand leading to lower strengths. There is no evidence to suggest that the carbon itself is detrimental to the strength. It is only the secondary effect of increased water demand that causes the problem. It is quite likely that high-carbon ashes (greater than 5 % carbon) could be used in conjunction with water-reducing admixtures without resulting in any detrimental effect on concrete strength.
- There is no evidence to suggest that the 45-µm sieve residue test is a good indicator of fly ash quality. Results are reported in which ashes with as high as 30 % of particles above 45 µm (more than twice the 12,5 % limit) have been used without any significant increase in water demand, and no correlation was found between 45-µm sieve retention and strength. Other researchers that did report a reduction in strength with higher 45-µm residue had to increase the water content to maintain constant workability, and it is reasonable to assume that reduction in strength was as a result of the increase in water and not of the coarseness of the ash *per se*.
- The limit of cement replacement by ash is normally specified at 30 %. The use of large percentages of ash does result in reduced early strengths but the later-age strength is often enhanced. For specific applications there could well be benefits to be gained in replacing high percentages of cement with ash.
- It would be unwise to judge the quality of an ash largely on the basis of its carbon content and 45-µm sieve retention. Each source of ash should be tested for performance in concrete with a particular cement source. This should be done on all those South African fly ashes currently deemed unfit for use in concrete to establish whether or not they are in fact suitable for use.

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