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USE OF PORTLAND PFA CEMENT IN COMBINATION WITH SUPERPLASTICIZING ADMIXTURES

R.K. Dhir, W.Z. Zhu, and M.J. McCarthy[1]
Concrete Technology Unit, Department of Civil Engineering, University of Dundee,
Dundee DD1 4HN, Scotland, UK

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ABSTRACT

The results of a test programme undertaken to achieve parity between concretes made with Portland cement (PC, Class 42.5 N) to BS 12 and Portland pulverized-fuel ash cement (PPFAC) to BS 6588 at equivalent cement content, by controlling the water content of the mix and the use of a superplasticizing admixture are described. With 27% PFA as a constituent of the cement, parity at 28 days was achieved at water contents of between 145 and 160 kg/m^3, depending on the cement content. A mix design chart is developed from the data to illustrate how the water and PPFAC contents of concrete can be adjusted to achieve a particular design strength. Issues relating to practical aspects of use are also considered. © *1998 Elsevier Science Ltd*

Introduction

The use of pulverized-fuel ash (PFA) as a constituent of cement in concrete construction is now well established, with coverage of the material given in most of the current or developing concrete design and specification standards. Indeed, it has been demonstrated that in almost all respects, similar or enhanced performance to that of Portland cement (PC) concrete is achievable with PFA at levels of up to 45%, providing concrete of equivalent 28-day strength is produced (1–5).

The characteristics of PFA are, however, different to those of PC. For example, lime (normally from cement hydration) is required to initiate reactions, which tend to occur at a slower rate than PC, but over a longer time period. Therefore, in meeting a required strength, these factors need to be taken into account in the mix proportioning.

The most widely used technique in achieving this is to simply increase the total cement content of the mix and this approach is followed in existing mix design methods (6). While this is satisfactory, it is possible, particularly for mid- to high-range cement content mixes, that the increasing fines content and mix water demand may cause the cement and water to work less effectively together. Indeed, with the need to prevent agglomeration of the cement particles and to provide the necessary workability and achieve the required strength, it may

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[1]To whom correspondence should be addressed.

not be possible by simple increases in cement content. An alternative to this lies in reducing the mix water content and using superplasticizing admixtures. In keeping the cement content fixed, this maximises the efficiency and contribution of cement to concrete and there is also evidence to suggest that this approach may be of benefit to performance (7,8).

In view of the developments in pre-blended PFA cement production in the UK (conforming to BS 6658 (9) or BS 6610 (10)) and the introduction of European cement standards which include such cements, optimising their use is becoming of increasing importance.

This paper explores what can be achieved through the use of Portland pulverized-fuel ash cement (PPFAC) to BS 6588 (i.e., PFA levels upto 35%) and superplasticizing admixtures in concrete. Consideration is given to the achievement of parity with a PC concrete at a given cement content with a mix containing PPFAC, by controlling the water contents to achieve equal design strength. The technical and economic issues relating to the use of PPFAC are also discussed.

Experimental Details

Materials

The cements comprised a Portland cement (PC, Class 42.5 N) to BS 12 (11), used as a reference and dry blended with a PFA to BS 3892, Part 1 (12) in the ratio of 73:27, giving a PPFAC conforming to BS 6588 (9). Superplasticizing admixture to BS 5075, Part 3 (13) was used to maintain the workability level at 75 mm slump. The aggregate comprised natural gravel of 20 mm maximum size and sand to zone M of BS 882 (14).

Mix Proportions

The PC concrete mixes, designed with cement contents from 250 to 500 kg/m^3 in increments of 50 kg/m^3, were used as a reference (referred to as PC 185 mixes). For these, the free water and coarse aggregate contents were fixed at 185 and 1260 kg/m^3 respectively, and the sand content adjusted to maintain the yield. Four series of PPFAC concrete mixes, with the same binder content range (250 to 500 kg/m^3), but reduced water contents of 175, 165, 155, and 145 kg/m^3, were tested (referred to as PPFAC 175, PPFAC 165, mixes etc). The superplasticizing admixture was used in the mixes containing water at 165, 155, and 145 kg/m^3 at various dosages to achieve the required workability and aggregate contents adjusted to give the correct yield. A summary of the mix proportions is given in Figure 1.

Test Procedures

Standard strength testing was carried out at ages 2, 7, 28, days and 3, 6, and 12 months. Initial surface absorption test (ISAT) and air permeability test measurements were made on selected specimens to provide comparisons between different means of proportioning PFA mixes. These followed the methods described in BS1881 (15) and by Dhir et al. (16) respectively. The specimens used for these tests were also water cured at 20°C to 28 days, followed by pre-conditioning through oven-drying to constant weight at 105°C. Tests from related studies covering other concrete properties, mainly durability, were also used to compare different

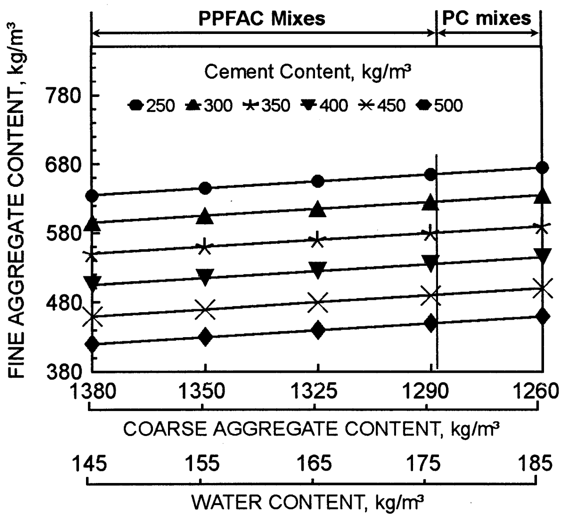

FIG. 1.
Mix proportions for PC and PPFAC concrete mixes.

methods of mix proportioning. In these cases, the concretes were again all water-cured at 20°C to 28 days before testing, using either standard tests or methods developed at the University of Dundee, the details of which are given in the appropriate references.

Cube Strength/w/c Ratio Relationships

Figure 2 shows the 28 day cube strength vs. water/cement (w/c) ratio relationships. This demonstrates that, as expected, the PC concrete exhibited a higher strength at a given w/c ratio than the PPFAC concrete and that all PPFAC concretes, irrespective of water content, followed a single relationship. The suggestion for the low water content mixes that the results lie at the lower part of the relationship indicates that a water level of 145 kg/m^3 is perhaps the lower limit for the water content with the admixture used. However, recent developments suggest that a new generation of superplasticizing admixtures are becoming available, which may enable further water reductions below the 145 kg/m^3 level to be achieved.

Achieving Strength Parity with PC Concrete

Figure 3 shows, as a typical example, the strength development of various PPFAC and corresponding PC concrete mixes with a binder content of 350 kg/m^3. As expected, the PPFAC concrete mix without superplasticizing admixture and water content of 175 kg/m^3 (PPFAC 175) had lower strengths than the PC mixes at early ages, with equal strength being achieved at just before 1 year. With reductions in water to 165 and 155 kg/m^3, equal strength was achieved at approximately 90 and 28 days respectively. At a water content of 145 kg/m^3,

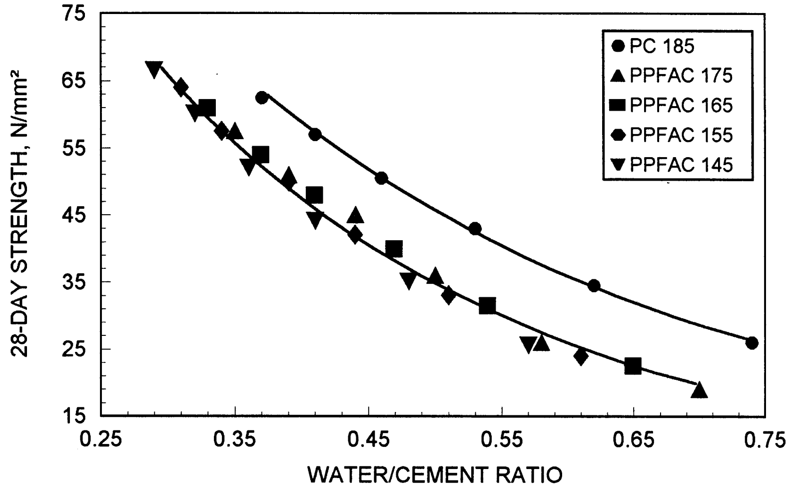

FIG. 2.
Relationship of 28-day strength and water/cement ratio.

equal strength was reached almost immediately. For all PPFAC/superplasticized mixes, significantly greater strength than that of the PC mix was obtained in the longer term.

The results for the range of PPFAC contents are shown in Figure 4, which gives strength equality lines with respect to PC concrete at corresponding cement contents. The results indicate that the cement content of the concrete mixes influenced the relative strength development of the PPFAC mixes at a given water content. In general, comparable strengths to those of the reference PC 185 mixes were achieved earlier in higher cement content mixes.

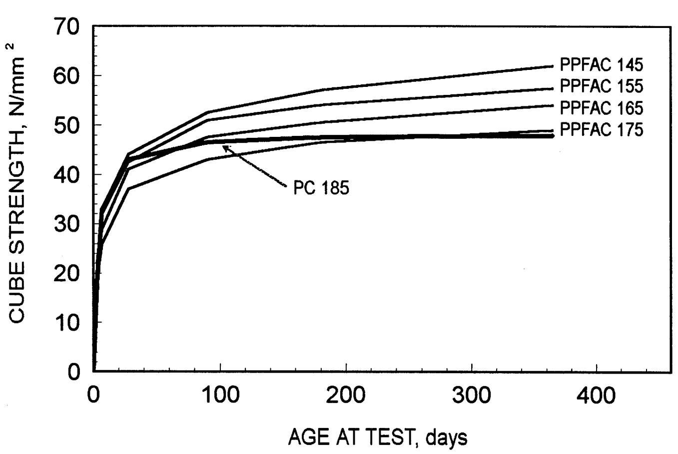

FIG. 3.
Strength development of PC and PPFAC mixes.

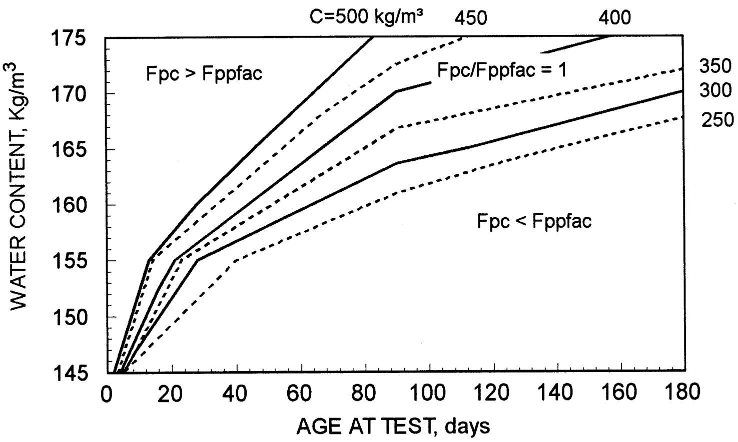

FIG. 4.

Equality lines of relative strength for PPFAC mixes, with respective to PC 185 mixes at equal content.

The results also demonstrate the effect of water content on strength development, with equivalent strengths to those of the corresponding PC 185 mixes being achieved earlier at lower water contents. Therefore, from a practical point of view, if early strength is important, the use of PPFAC at equivalent cement content to PC, should use a low water content.

Selection Of PPFAC Mix Proportions for Strength

Based on the results obtained from Figure 2, the mix design chart covering cement and water contents for a range of 28 day design strengths and PPFAC concretes has been developed, as shown in Figure 5. The required cement contents for the different water contents are also given in Table 1. These illustrate the options available for mix proportioning of PPFAC concrete and indicate that there is a 10 to 15 kg saving in cement with each 5 l/m^3 reduction in water content. The results also indicate that parity of cement contents is achieved at higher water contents as the concrete design strength increases, suggesting that the PFA constituent contributes more effectively at higher cement contents, Table 1.

The results also show that the practical range of cement contents can be used to achieve the corresponding range of design strengths with PPFAC. The choice of PPFAC and water contents, however, will be influenced by technical performance and the relative costs of the PC, PFA and superplasticizing admixture available.

Technical Performance

The performance of concrete, in terms of its permeation characteristics, using the method described above and that of PFA concrete proportioned by other means, are given in Table 2. These include increased binder content and the use of high early strength cement (17), which represents a further option in achieving strength parity with PPFACs. The results show

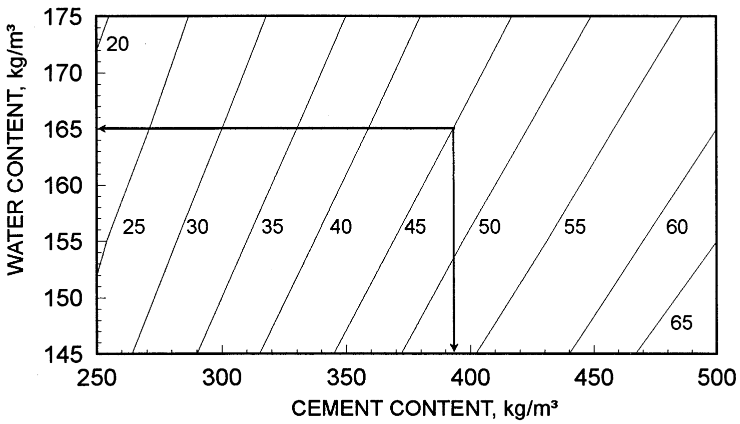

FIG. 5.
Chart for establishing mix proportions for PPFAC concrete of required 28-day strength (in N/mm^2).

that all equivalent PPFAC concrete mixes had reduced initial surface absorption and air permeability values compared to their corresponding PC mixes. The most significant reduction in ISAT-10 value, of approximately 30%, was observed for the concrete mix using PPFAC/superplasticizing admixture, while the mixes following the other two methods, showed smaller relative reductions of about 10%. The air permeability results followed a similar ranking to that for the ISAT-10, although in this case, slightly greater relative reductions were obtained for all PFA concretes.

The results suggest that the benefits associated with PPFAC and superplasticizing admixtures in the refinement of the concrete microstructure through the densifying effect of the fine material and improved dispersion and microstructure development with the admixture (7), are cumulative and the combination of the two is an effective means of enhancing durability potential.

TABLE 1
Cement content required for PC and PPFAC concretes to achieve given 28-day design strengths at different water contents.

28-day cube	PC	PPFAC						
strength	185	175	170	165	160	155	150	145
20	225	255	250	245	235	–	–	–
30	270	320	310	300	290	280	275	265
40	335	380	370	360	350	335	325	315
50	400	450	435	425	410	395	385	370
60	475	530	515	500	485	470	455	440

–, less than 225 kg/m^3.

TABLE 2
Results of initial surface absorption and air permeability of PC control and equivalent PPFAC mixes (nominal slump = 75 mm, and 28-day strength = 42 MPa).

Mixes of equal slump and 28-day strength	Mix proportions, kg/m^3			Results relative to PC control, %	
	PC	PPFAC	Water	ISAT-10	Air permeability
PC control	350	–	185	100	100
Use of higher total binder content	–	415	175	88	81
*Use of high early strength PC	–	350	175	85	61
Use of water reducing agent	–	350	155	70	49

* A mineralized cement clinker with high C_3S content was used.

This is further demonstrated in Table 3, which gives a summary of the findings of a number of studies that have been carried out at the University of Dundee and have mostly considered PPFAC concrete mixes of equivalent w/c ratio and strength, but with the use of superplasticizing admixtures to maintain workability (7,18,19). These indicate that for properties where reduced cement contents might be expected to be of benefit, i.e., heat of hydration and drying shrinkage, better performance was noted. For durability, as mentioned above, improvements in permeation were obtained and this was also found for deterioration processes which are predominantly physical, i.e., freeze/thaw resistance. In the case of carbonation and chloride ingress, which are influenced both by the physical and chemical characteristics of concrete, essentially similar or slightly improved resistance was found, depending on the design strength considered.

Economic Issues

It is difficult to give a meaningful cost comparison for the two sets of concrete mixes, as the constituent material properties and products vary in performance and cost. For the materials used in the study, the cost for a given design strength was found to be approximately constant

TABLE 3
Summary of research findings on the effect of water reduction on properties of equivalent concrete mixes.

Property	Effect of water reduction (at equivalent w/c ratio)
Heat of hydration	reduced at all levels
Drying shrinkage	reduced at all levels
Permeation	reduced at all levels
Carbonation resistance	similar performance
Chloride resistance	minor improvement depending on design strength
Freeze/thaw resistance	improvement at all levels

across the range of water contents used, based on the costs quoted by the material suppliers (bulk list, ex works)

The paper has demonstrated that this method is a technically effective means of proportioning PPFAC concrete and provides scope for concrete producers to find their optimum cost, within a water content range, for their locally available materials. It should be borne in mind that in some cases, increased cement content to achieve parity of strength may economically be the best route.

Conclusions

PPFAC can be used at the same cement content as PC in concrete by reducing the water content of the mix using superplasticizing admixture, with parity in strength development achieved at different ages. A strength chart has been developed to illustrate mix options through adjustment to the water and cement contents for PPFAC concrete. This illustrates that parity of 28 day strength at the same cement content as PC is achieved at water contents of between 145 and 160 kg/m^3, across the range of practical cement contents.

From a technical viewpoint, the use of PPFAC and superplasticizing admixture and reduced water contents in the mix can be beneficial to concrete performance and this generally applies across the whole range of properties, including aspects of durability. With the verification of suitability of the method, this should potentially broaden material selection for concrete specifiers and producers with PPFAC.

Acknowledgments

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References

1. R.K. Dhir et al., Cem. Concr. Res. 18, 277–289, (1988).
2. R.K. Dhir et al., Int. Cem. Rev. 75–81, (1992).
3. M.D.A. Thomas et al., Build. Res. Est. IP/11/91. (1991).
4. R.K. Dhir et al., Proc. Inst. Civ. Engs., Struct. & Blds. 94, 3, 335–342, (1992).
5. V. Sivasundaram et al., ACI Mater. J. 88, 4, (1991).
6. D.C. Teychenne et al., Build. Res. Est. (1988).
7. R.K. Dhir et al., Int. Conf., ACI SP 100, J. Scanlon (ed.) 1, 741–764 (1987).
8. T.A. Harrison, ACT course lecture notes (1997, to be published).
9. British Standards Institution. BS 6588, (1996).
10. British Standards Institution. BS 6610, (1996).
11. British Standards Institution. BS 12 (1996).
12. British Standards Institution. BS 3892, Part 1 (1997).
13. British Standards Institution, BS 5075, Part 3 (1985).
14. British Standards Institution, BS 882, (1983).
15. British Standards Institution, BS 1881, Part 5, (1970).
16. R.K. Dhir et al., Mag. Concr. Res. 41, 147, 87–97 (1989).
17. R.K. Dhir et al., Struct Eng. 71, 8, 139–145, (1993).
18. R.K. Dhir et al., Cem. Concr. Res. 26, 1761–1766, (1996).
19. R.K. Dhir (1998, in preparation).