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Communication

Mix proportioning and engineering properties of conditioned PFA concrete

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Abstract

This paper describes the mix design procedure developed for use with conditioned (moistened) pulverized-fuel ash (PFA) in structural concrete. It is shown that a given strength can be achieved with conditioned PFA concrete with some reduction in w/c ratio, compared to equivalent dry PFA mixes. The adjustment required is progressive with conditioned PFA storage period (up to 6 months), but is not influenced significantly by either dry PFA characteristics or conditioning/storage variables. For a given strength, the development of compressive strength (up to 180 days), flexural strength, modulus of elasticity (E), drying shrinkage (ξ_S) and creep (ξ_C) are essentially the same for dry and conditioned PFA mixes. The practical implications of the work are presented.

Keywords: Compressive strength; Fly ash; Moist storage; Mechanical properties; Concrete

1. Introduction

Pulverized-fuel ash (PFA), in dry form, is used increasingly as a cementitious material in structural concrete, offering a number of technical and economic benefits [1]. However, handling and storage requirements mean that, following production, significant quantities of PFA are either conditioned (moistened with a controlled amount of water) and stockpiled, or pumped as slurry to ponds (lagoons). In this form, the majority of national standards consider PFA unsuitable for use as a cementitious material, which appears to relate to essential requirements for dry storage of Portland cement (PC). Moreover, much of this material remains unused and requires disposal.

The feasibility of using conditioned PFA as a cementitious component in concrete has recently been established by the authors [2,3]. However, to bring the material to the point where it can be used in engineering practice requires that (i) the minor effects of moistening and storage identified, are accommodated within a mix proportioning procedure, and (ii) the wider range of structural concrete properties are examined. These issues are covered in this paper.

2. Materials

Samples of three dry PFAs (PFAs 1 to 3) were obtained for the main part of the work, with fineness between approximately 5.0% and 30.0% retention on a 45-μm sieve. Samples were conditioned (to 10% moisture level by dry mass) using mains water at 20°C, with the material subsequently stored at 20°C in airtight containers for either 1 or 6 months, prior to testing [2]. Mains water was used also for mixing and testing of concrete specimens. All PFA samples were characterised for fineness and loss-on-ignition (LOI) [4], following oven-drying at 105°C to constant mass, with bulk oxide composition determined by X-ray analyses [2]. Table 1 gives the main properties of the dry and conditioned materials, and includes details of the PC-42.5N [5]. As reported previously [2], conditioning and storage led to progressive increases in PFA coarseness and LOI, reflecting particle agglomeration and uptake of water, whilst bulk oxide composition remained essentially unchanged.

Natural gravel in 20- and 10-mm fraction sizes and sand of zone M, all conforming to BS 882 [6], were used in a surface dry condition. A superplasticizer conforming

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Table 1
Main properties of dry and moistened PFAs and PC used in study

	Fineness, % retention at 45 μm			LOI, %			Main bulk oxide composition (dry materials), %							
	Dry	1 month[a]	6 months[a]	Dry	1 month[a]	6 months[a]	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O
PFA 1	4.8	18.0	34.5	5.2	5.3	6.0	41.3	40.7	5.0	2.5	0.5	0.2	0.7	0.1
PFA 2	14.6	36.2	36.4	7.5	8.1	8.2	51.3	23.7	6.9	2.1	0.8	0.2	3.6	2.3
PFA 3	29.6	31.8	40.1	3.7	3.8	3.9	52.0	27.2	6.7	2.1	0.6	0.3	3.5	2.1
PC[b]	350[c]	–	–	1.2	–	–	22.8	5.2	1.2	62.2	3.4	2.7	0.9	0.3

(–) Not applicable.
[a] Storage period (months) at 20°C of moistened PFA (10% moisture by dry mass).
[b] PC-42.5 N (BS 12).
[c] Specific surface area, m^2/kg.

to BS 5075: Part 3 [7] (relative density 1.17 at 20°C, nil chloride content) was used to fix the workability of the concrete mixes.

3. Test methods

Concrete was produced in the laboratory using a forced action mixer, and tested immediately for workability using the slump test. Fresh concrete was cast into steel moulds, which were initially stored for 24 h under damp hessian and plastic sheeting. After demoulding, specimens were water-cured at 20°C until testing for hardened properties, including compressive strength (at ages up to 180 days), flexural strength (28 days) and static modulus of elasticity in compression (E) (28, 90 and 180 days). These tests were carried out in accordance with the relevant parts of BS 1881 [8]. Drying shrinkage (ξ_S) was determined by measuring periodically the length of 3-day water-cured prism specimens 50 × 50 × 200 mm during storage in air at 20°C/55% RH [9]. Creep strain (ξ_C) was similarly determined using 28-day water-cured sealed cylinder specimens 100 mm diameter × 300 mm, whilst subject to constant stress of $0.50f_{cu}$ (f_{cu} measured using 100-mm cubes) [9]. Any slight drying shrinkage was accounted for by parallel measurements on similarly prepared, but unstressed, specimens, and creep coefficients calculated.

4. Development of concrete mixes with conditioned PFA

To establish the mix proportions required to achieve 28-day cube strengths of 25, 35, 50 and 60 N/mm^2, concretes having a range of w/c ratios were cast. At each w/c ratio, the same mix proportions were used for all PFAs and each moisture/storage condition. When using conditioned PFA, adjustments were made to ensure that the PFA (dry mass) and free water contents in the mix were equal to those of dry PFA concrete. All mixes were superplasticized to give workability of nominal 75-mm slump, with the dosage required (e.g., 0.50% to 1.25% by mass of cementitious material for PFAs 1 to 3) tending to increase with reducing w/c ratio. It was noted that dosages were essentially the same for dry and conditioned PFA concretes, which, given the agglomeration in conditioned PFA, is perhaps surprising. However, it appears that the dispersing effect of the chemical admixture reduced or eliminated any differences [10], whilst PFA agglomerates may also break down in the concrete mixer [3].

For a given PFA, the strength results obtained were plotted against w/c ratio, and a best-fit curve applied for each moisture/storage period condition, Fig. 1. From the curves, the w/c ratios necessary to achieve the required strengths were established, see Table 2 for 35-N/mm^2 strength (PFAs 1 to 3). For dry PFA concrete, the w/c ratio required for a given strength was, in the main, slightly lower with coarser material, as expected [11]. Conditioning and increasing storage of PFA tended to give slight, but progressive, reduction in w/c ratio. This probably reflects the particle agglomeration and chemical activity occurring during storage of PFA [2], although the former may be offset slightly by partial breakdown of PFA agglomerates during concrete production, as suggested previously [3].

Table 2 also gives w/c ratios determined for 35-N/mm^2-strength concretes made with CUTs 1 to 3 (PFA obtained

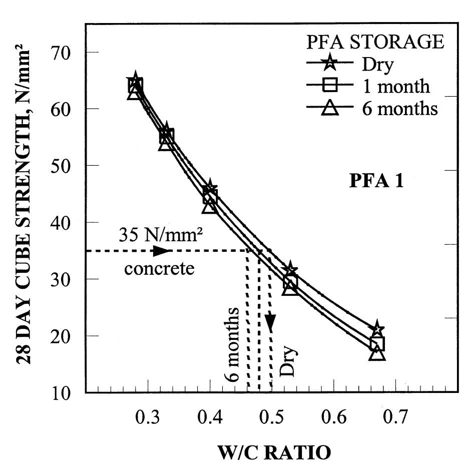

Fig. 1. Influence of PFA conditioning and storage on the w/c ratio required to achieve a given 28-day compressive strength (PFA 1 concrete).

Table 2
Influence of dry PFA characteristics and moistening/storage variables on w/c ratio required to give 35-N/mm^2 concrete

	Dry PFA characteristics							
	Fineness (several sources)			Fineness (single source[a])			High LOI[b]	High Lime[c]
PFA storage period, months	PFA 1	PFA 2	PFA 3	CUT 1	CUT 2	CUT 3	PFA 4	PFA 5
Dry	0.50	0.52	0.48	0.50	0.46	0.46	0.45	0.46
1	0.48	0.48	0.43	0.45	0.46	0.45	0.48	0.45
6	0.46	0.47	0.46	0.45	0.45	0.42	0.45	0.44

All PFA moistened with mains water (pH 7) and stored in the laboratory at 20°C.
[a] Classified PFA from single source: Fineness = 5.3 (CUT 1), 16.4 (CUT 2), 29.1 (CUT 3) % retention at 45 μm; LOI ≈ 3.0%; CaO ≈ 3.0%.
[b] Fineness = 15.1% retention at 45 μm; LOI = 10.6%; CaO = 2.7%.
[c] Fineness = 17.3% retention at 45 μm; LOI = 4.0%; CaO = 4.4%.

from a single source, i.e., having similar chemistry, and classified into fractions of differing fineness), PFA 4 (high LOI) and PFA 5 (high lime content). The data indicate that, whilst the w/c ratio of concrete varied with the properties of the PFA, the effects of conditioning and storage were similar for each PFA source [2,12]. Similar trends were observed following tests carried out using a range of PFA conditioning/storage variables, including moisture content (10% and 20%), properties of the conditioning solution (pH 5 to 8 and seawater), storage temperature (5 and 20°C) and storage regime (laboratory and power station stockpile) [12].

5. Concrete mix proportioning procedure

In view of the trends observed in the data given in Table 2, relationships between required w/c ratio and PFA characteristics were investigated. It was found that, for a given strength, w/c ratio was related to the 45-μm sieve retention measured for the PFA in the state it was in at the time of use, whether dry or conditioned and stored, see Fig. 2(a) for PFAs 1 to 3. It was also noted that the gradients of the lines on this graph were relatively shallow, compared to those established in related work considering dry PFA [11]. This appears to be related to the partial breakdown of conditioned PFA agglomerates to effectively finer material during mixing of concrete [3]. From the relationships of Fig. 2(a), a method was developed to accommodate the influences of moisture addition to PFA in the concrete mix design procedure, as follows;

Step 1: A w/c ratio–strength curve constructed for dry PFA of fineness 5.0% retention at 45 μm, Fig. 2(b) is used to establish the w/c ratio required to achieve a given strength.

Step 2: A correction factor, F, related to the fineness measured for conditioned PFA, is applied to this w/c ratio, Fig. 2(c). For example, for conditioned PFA having 45-μm sieve retention of 35.0% (i.e., typical for a BS 3892: Part 1 PFA after wet storage for 6 months, see Table 1), the correction factor, F, would be 3.3×10^{-2}. Given this, a w/c ratio of 0.48 would be required to produce a 30-N/mm^2-strength concrete, compared to 0.50 for material having 5.0% retention at 45 μm. Thus, as for dry PFA, measurement of the fineness of conditioned PFA can be used to allow appropriate adjustment to the w/c ratio of the mix.

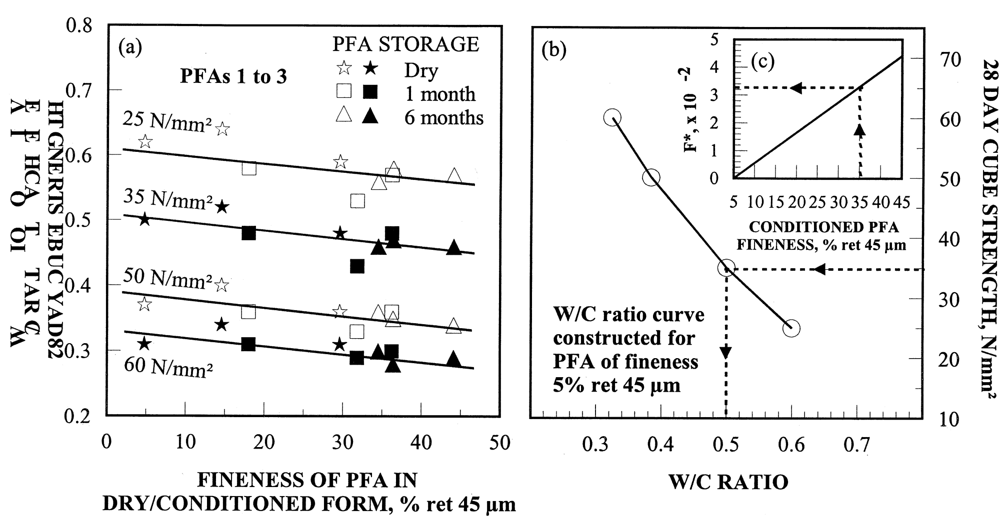

Fig. 2. *F = correction factor to w/c ratio based on fineness (45 μm sieve retention) of conditioned PFA: $W/C_{\{\text{conditioned } PFA\}} = W/C_{\{5\% \text{ ret } 45\ \mu m\}} - F \times W/C_{\{5\% \text{ ret } 45\ \mu m\}}$. Development of mix design procedure for conditioned PFA concrete.

Table 3
Concrete mix proportions (kg/m^3) determined for use with dry PFA 1

Strength, N/mm^2	W/c ratio	PC	Dry PFA	Free water, l/m^3	SP, % total cement	Aggregates		
						20 mm	10 mm	Sand
25	0.62	185	80	165	0.50	810	410	705
35	0.50	230	100	165	0.50	810	410	645
50	0.37	310	135	165	0.75	810	410	555
60	0.31	370	160	165	1.00	810	410	455

All mixes having 30% PFA level and workability 75-mm nominal slump.

Step 3: The corrected w/c ratio can then be used with conventional methodologies to establish the overall mix proportions.

6. Engineering properties of conditioned PFA concrete

Having established the w/c ratio required to give strengths between 25 and 60 N/mm^2, overall mix proportions were established to consider the influence of PFA conditioning and storage on other concrete properties at equal strengths. As an example, Table 3 gives the mix proportions used for dry PFA 1 concrete. For the other concretes, the w/c ratio was adjusted (as described above) via the water content, with sand content adjusted to maintain concrete yield. For engineering properties other than compressive strength development, tests were carried out using PFAs 1 and 3 only.

6.1. Compressive strength development

Testing of strength development to 180 days indicated that, for a given 28-day strength (25 to 60 N/mm^2), strengths at other test ages were essentially similar between dry and conditioned PFA mixes, see Fig. 3 for PFA 1, with differences noted within limits expected for test variation [12]. This was observed for PFAs 1 to 3, CUTs 1 to 3 and PFA 4 (high LOI). For high-lime material (PFA 5), slightly reduced strength gain after 28 days was noted following conditioning, compared to dry PFA concrete, with strength differences of up to 5.0 N/mm^2 noted at the age of 180 days when using material stored for 6 months.

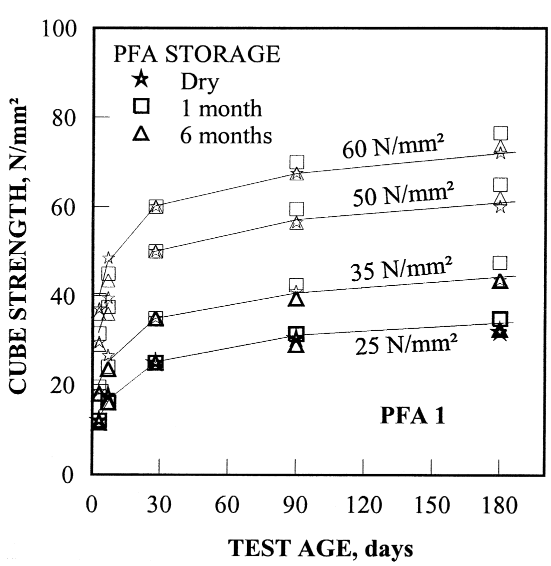

Fig. 3. Strength development of conditioned PFA concrete.

6.2. Flexural strength

The results indicate that neither PFA fineness nor conditioning and storage had any significant influence on the relationship between 28-day compressive and flexural strengths, with values of approximately 3.5 N/mm^2 obtained for the latter for 35-N/mm^2 concrete, Table 4. Indeed, the variations of ± 0.3 N/mm^2 or less noted following conditioning are again likely to be due to test variation [12].

6.3. Static modulus of elasticity in compression (E)

The 28-day modulus for 35-N/mm^2 strength concrete was typically 22.0 kN/mm^2, with PFA fineness and conditioning/storage period having little influence, Table 4, as noted for flexural strength. At later test ages (up to 180 days), *E* increased progressively, as expected, with the rate of change comparable to that noted for compressive strength, see Fig. 4. Furthermore, for a given cube strength, *E* remained within the BS 8110: Part 2 limits. Again, the variations occurring following PFA conditioning (± 1.0 kN/mm^2 or less at 28 days, compared to dry PFA concrete) are not practically significant [12].

6.4. Drying shrinkage (ξ_S)

For dry PFA concrete of strength 35 N/mm^2, shrinkage was slightly lower with the coarser PFA 3, Table 4. For conditioned PFA concrete, at the same strength, shrinkage tended to be reduced marginally, i.e., after 48 weeks drying, (15 to 30) $\times 10^{-3}$ strain reduction compared to dry PFA concrete, but conditioning storage period had no clear influence. Whilst relatively minor, the observed influences on shrinkage of PFA fineness and moistening may partly reflect changes in concrete

Table 4
Flexural strength, modulus of elasticity (*E*), drying shrinkage and creep of dry and moistened PFA concretes (strength 35 N/mm^2)

PFA	Flexural strength (28-day), N/mm^2			*E* (28-day), kN/mm^2			Drying shrinkage (48 weeks), $\times 10^{-3}$			Creep coefficient (24 weeks)		
	Dry	1 month[a]	6 months[a]	Dry	1 month[a]	6 months[a]	Dry	1 month[a]	6 months[a]	Dry	1 month[a]	6 months[a]
1	3.4	3.6	3.7	22.5	23.0	21.5	123	93	104	1.15	1.08	1.22
3	3.6	3.5	3.5	22.5	22.5	21.0	114	99	88	1.40	1.12	1.30

[a] Storage period (months) at 20°C of conditioned PFA (10% moisture by dry mass).

microstructure due to the slight adjustments made to w/c ratio.

6.5. Creep (ξ_c)

For dry PFA concrete of strength 35 N/mm^2, creep coefficients were comparable between the fine and coarse materials tested, Table 4. Similarly, PFA conditioning and storage had little or no clear influence on creep, with changes typically ± 0.10 or less, compared to dry PFA concrete. It appears, in this case, that the point of water addition to PFA, and the slight adjustments made to the mix proportions when using conditioned material, had little influence on the property.

7. Conclusions and practical implications

For concrete containing conditioned PFA, a slight reduction in w/c ratio was required to achieve a given strength, compared to an equivalent dry PFA mix, although this had little effect on super-plasticizer dosage requirements. A procedure has been established to allow adjustment to the w/c ratio based on PFA fineness measurements when the material is conditioned, which can then be used within existing design methods to establish overall mix proportions. For low-lime material conditioned and stored for up to 6 months, the properties of the PFA used appear to have little influence on the adjustment required to w/c ratio. For high-lime PFA, this period of equivalence is limited to approximately 3 months [12].

At a given strength, early rates of strength gain are essentially the same for dry and conditioned PFA mixes. The use of conditioned PFA, therefore, has no implications for striking form work times, early-age thermal cracking, etc. Under good curing, the long-term benefits to strength development associated with dry PFA are essentially maintained with conditioned material, although a slight adverse effect may be observed with high lime material, with this effect being progressive with storage period.

At a given compressive strength, flexural strength, modulus of elasticity, drying shrinkage and creep are essentially similar between dry and conditioned PFA concretes.

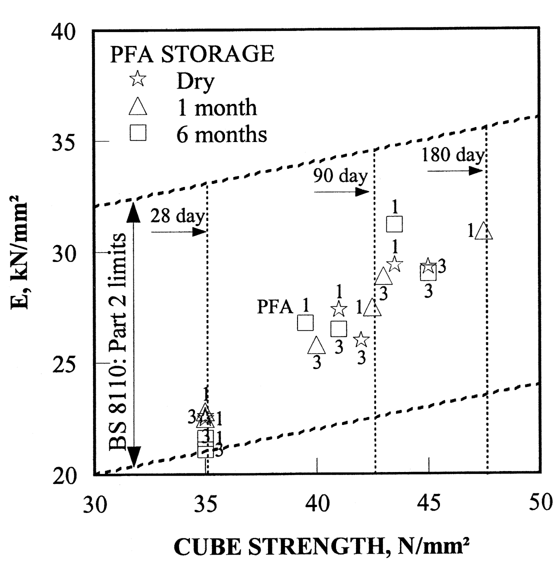

Fig. 4. Relationship between *E* and compressive strength.

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