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Sourcing Fly Ash for Use in Concrete from Stockpile Deposits

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ABSTRACT

The article describes a study carried out to investigate the effects of storing fly ash wet in stockpiles on the characteristics of the material and potential for recovery and use in concrete. It is shown that changes in fly ash, including the formation of agglomerates and surface products on particles, occur, which can affect the properties of concrete. Processing of the fly ash by drying/de-agglomeration, particle separation, size reduction and carbon removal at both laboratory and larger (pilot/benchtop) scales is described. As well as giving satisfactory handling properties, treated material was also able to meet Standard requirements in some cases. The role of particle size following processing on behaviour in mortar and concrete is considered, with benefits generally being achieved as this reduced. Further research is required to investigate some outstanding issues, including durability, however, the work to date gives encouraging results towards the use of wet stored fly ash in concrete construction.

Keywords: Concrete, Fly Ash, Stockpile Deposits

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1 Introduction

The last decade or so has seen a gradual reduction in electricity generation by coal, with alternative fuels and technologies increasingly finding use [1]. This is affecting the availability of dry fly ash for concrete, which can provide benefits to fresh and hardened properties, as well as reducing environmental impact [2]. Alternative means of sourcing fly ash are, therefore, receiving increasing attention, with material held in wet storage, e.g., stockpiles, offering a possible option [3]. This exists since the supply of fly ash in some regions has frequently exceeded demand, with the surplus often kept in these types of area. In the UK, quantities of around 100 Mt are believed to be available for recovery [4].

Wet stored fly ash may be at the coarser end of the particle size range and have relatively high unburnt carbon contents [5]. In the presence of moisture, particle cohesion can develop and with chemical processes occurring, lead to agglomeration in the material and changes in particle surface characteristics (e.g., formation of secondary mineral products) [6, 7]. These have been noted to affect handling, as well as the properties of concrete containing the material, e.g., workability and strength [7]. Given the influences and variability sometimes observed in wet stored fly ash, processing to achieve suitable properties for use in concrete is likely to be necessary. This article reviews the outcomes of a research programme examining the effects of wet storage on (low lime) fly ash properties and potential for recovery and processing for use in concrete.

2 Wet storage effects

Fly Ash Properties

To investigate wet storage effects, four laboratory-moistened (10% by dry mass)/stored (sealed in bags/ containers at 20°C) fly ashes and those from eight stockpiles (storage history not known, moisture contents between 6 and 21%) were considered. These were from bituminous coal, except in one case which was anthracite (with drying (at 105°C), cooling and sealed storage carried out before testing). Key physical and chemical properties of three of the dry and laboratory-moistened fly ashes (stored to 730 days) are given in Table 1. These show that moistened fly ash coarsened (increased 45 µm sieve retention and median particle size (d_{50})) during storage, reflecting agglomeration, with greatest effects for initially finer material (DFA3).

The loss-on-ignition (LOI, normally used to assess carbon content) gave small increases with storage in some cases, appearing to relate to decomposition of products forming under wet conditions (e.g., sulfates, carbonates), with the high temperature (950°C) of the test [7]. The chemistry of the dry fly ashes was typically as expected for the coals used, with relatively low CaO contents, sum of the main oxides > 70%, alkalis (Na_2O_{eq}) < 3.3%, and sulfates < 2.0%. Small differences between these and the materials following wet storage were also found (Note: DFA5 was marginally below the 70% main oxides limit in BS EN 450-1 [8]).

The results from the range of stockpile fly ashes are also given in Table 1 and indicate that the materials were all relatively coarse (fineness between 41.1 and 62.3% retained on a 45 µm sieve) with low to high LOI (3.5 to 15.9%). These are likely to reflect the initial properties of the fly ashes and changes occurring during wet storage, as noted with the laboratory moistened materials. The chemistry was in general agreement with that obtained for dry and laboratory stored materials.

Table 1. Effect of wet laboratory storage on key properties of selected fly ashes

Property[2]	Dry and Laboratory Stored Fly Ash[1]						Stockpile Fly Ash SFA1 – SFA8
	DFA1	**DFA1 730 d**	**DFA3**	**DFA3 730 d**	**DFA5**	**DFA5 730 d**	
Physical and LOI							
Fineness[3]	33.9	59.2	5.7	45.6	18.4	36.4	41.1 – 62.3
d_{50}[4], µm	39.4	45.1	4.3	32.0	23.9	29.7	28.3 – 43.9
LOI	8.3	9.3	5.6	5.9	13.6	13.4	3.5 – 15.9
Chemical Composition							
CaO	4.5	5.4	3.1	3.4	2.2	2.1	2.1 – 4.4
SiO_2	47.9	46.3	50.1	49.2	41.3	40.1	41.2 – 51.2
Al_2O_3	20.3	20.1	22.4	22.9	23.4	22.2	19.5 – 25.2
Fe_2O_3	7.4	7.7	7.6	7.2	6.7	5.8	5.8 – 9.4
K_2O	2.2	2.1	2.5	2.8	2.3	1.6	1.7 – 2.8
Na_2O	1.5	1.1	1.7	1.3	0.7	0.6	0.7 – 1.1
SO_3	1.8	1.7	1.2	1.3	2.0	2.2	0.8 – 2.3

[1] 730 d sealed storage in the laboratory at 20°C

[2] Percent unless indicated otherwise

[3] Percent retained on a 45 µm sieve (Dry fly ash tested to BS EN 450-1, wet fly ash - mean of 6 tests)

[4] Median particle size

Tests for water requirement of fly ash and activity index with Standard mortars following BS EN 450-1 are given in Figure 1. These show that dry fly ashes gave values for water requirement between 97 and 104% (i.e., higher than the 95% limit for Category S (fine) fly ash in BS EN 450-1).

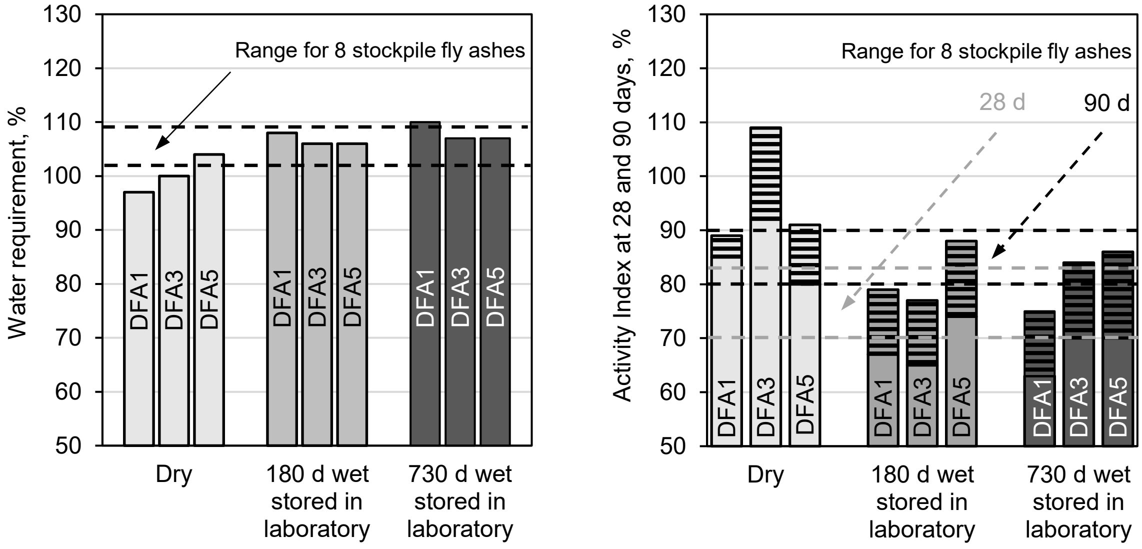

Figure 1. Effects of laboratory (10% moisture, 20°C) and stockpile storage on water requirement and activity index of fly ashes (shaded – 28 days; horizontal hatched 28 to 90 days)

There were increases with wet laboratory storage, which tended to develop with time, with values between 107 and 110% by 730 days. For stockpile fly ash, water requirements of between 102 and 109% were obtained. These effects are likely to reflect agglomerates forming/coarsening of the materials, and particle surface changes (products/roughening) as shown in Figure 2, for two of the stockpile fly ashes.

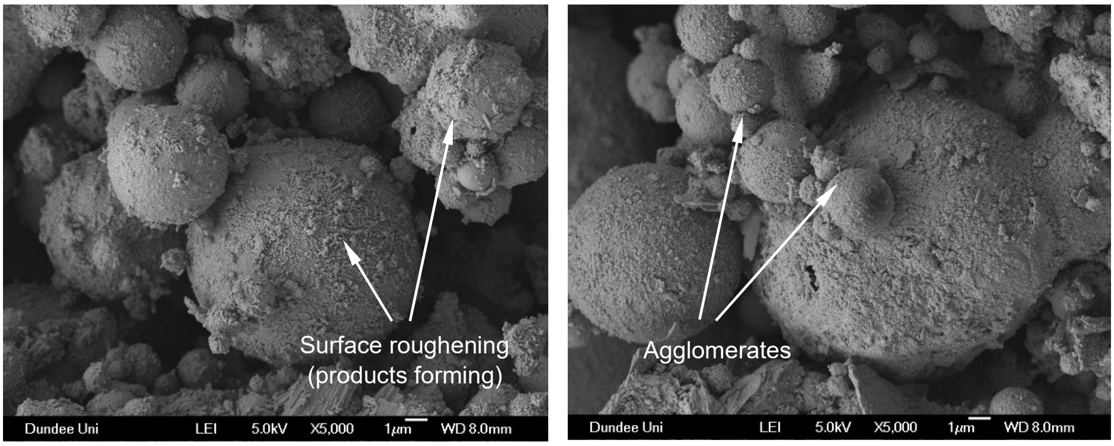

Figure 2. Examples showing morphology of SFA1 (left) and SFA2 (right) stockpile fly ashes

The activity index results, also in Figure 1, generally gave gradual reductions during wet laboratory storage, with the limits, of 75% by 28 days and 85% by 90 days in BS EN 450-1, only being met in one case (following 730 days) at the later age. Less than half of the stockpile fly ashes also met these at each test age. Related work [7] suggests agglomeration tends to occur in finer, more reactive, particles and hence fly ash containing increased quantities of these may be more greatly affected. It also appears that migration of lime to active surfaces (through products of the type shown in Figure 2 and from Portland cement hydration/fly ash reactions in the mortar) and changes in surface chemistry, during wet storage, may affect reactivity [9].

Concrete Properties

A concrete mix with a cement content of 350 kg/m^3 (with 30% fly ash in cement) and w/c ratio of 0.53 was used to investigate the wet stored fly ashes. This contained gravel aggregate (20 mm maximum size), a local sand, and had a fine to total aggregate ratio of 0.35. A polycarboxylate ether superplasticizing admixture (SP) was added to achieve a slump class of S3. This was used to provide a measure of wet storage effects on fresh concrete properties, with (100 mm) cube strength (following water curing at 20°C) measured at 28 and 90 days.

The results from the tests are given in Figure 3 and show increases in SP dose were required with laboratory wet storage to 730 days, compared to dry material, ranging from about 0.15% by mass cement for DFA3 and DFA5 to 0.40% for DFA1. There is, therefore, general agreement in ranking between water and SP dose requirements (in mortar and concrete). Comparisons with the SP dose range for a selection of the stockpile fly ashes indicate that these were also higher than for the dry materials. The wet storage effects noted for other fly ash properties (e.g., agglomeration, particle surface changes), therefore, appear to be reflected in the fresh concrete behaviour.

The concrete cube strength results are also shown in Figure 3 and mainly gave reductions in strength with wet storage of the fly ashes. These were least for coarser fly ash (DFA1), tending to increase with initial dry fineness, (8.0 and 10.0 MPa at 28 and 90 days for DFA3), and giving comparable results between the three wet stored materials at the two test ages and some similarities to the Activity Index data in Figure 1.

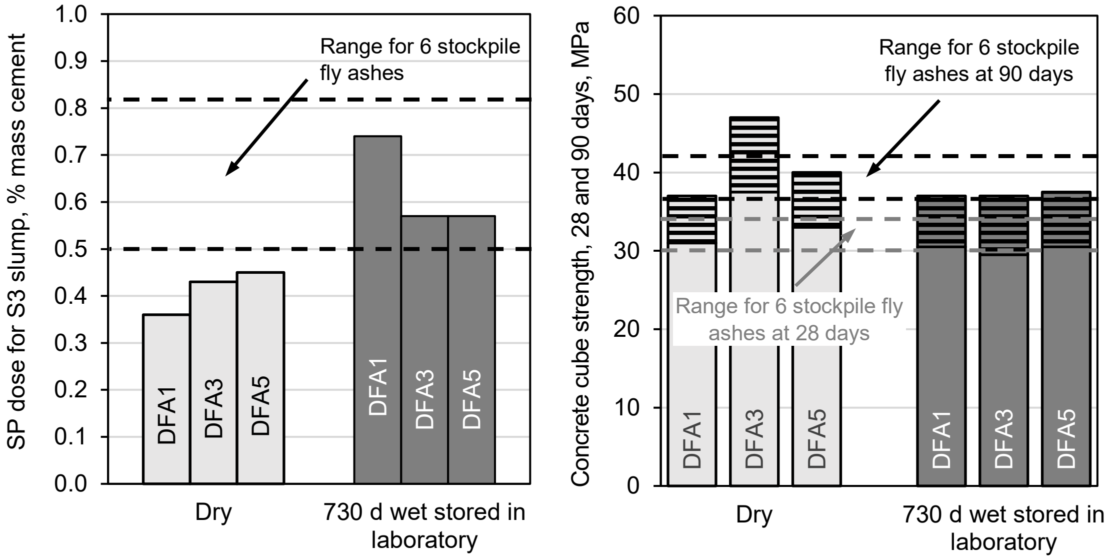

Figure 3. Effect of laboratory and stockpile storage on superplasticizer dose and cube strength of fly ash concretes (30% fly ash in cement, w/c = 0.53; shaded – 28 days; horizontal hatched 28 to 90 days)

Dry fine fly ash (DFA 3) concrete had higher cube strength than the stockpile materials considered, at both ages, but the other concretes, with wet or dry fly ash, were generally within the range for these. This highlights the effects of coarsening and similarity in laboratory wet stored and stockpile fly ash behaviour.

3 Laboratory processing of fly ash

The materials processed in the laboratory were those from the power station stockpiles and after initial drying were treated using the following techniques, (i) sieving (with both 600 µm and 63 µm sieves considered and the finer, passing, fractions tested – particle size separation); (ii) grinding in a ball mill (250 ml capacity, 6 × 20 mm hardened steel balls, 50 and 125 g sample loads – particle size reduction) and (iii) heat (thermal) treatment in a furnace (500°C for 1 hour). In some cases, for (ii) and for those of (iii), pre-treatment by sieving at 600 µm was used.

Fly Ash Properties

The results from a selection of fly ashes in Table 2 indicate that (i) gave little change in fineness for the coarser sieve (600 µm) but achieved values meeting Category S fly ash requirements in BS EN 450-1 with the finer sieve (63 µm; < 12.0% on a 45 µm sieve). For (ii) increased fineness was obtained (meeting Category S requirements by 20 minutes), which developed with extended periods in the ball mill (Table 2).

In both cases, there were changes in the LOI of fly ash, which are likely to reflect removal of components (for (i)) or opening of particle surfaces (for (ii)). There were relatively small differences in chemistry with particle separation and size reduction. Increases in fineness and reductions in LOI were obtained following heat treatment with little change in chemistry also noted.

Table 2. Examples of laboratory processing influences on key fly ash properties

Property[4]	Sieving[1]			Grinding[2]		Heat Treatment[3]	
	SFA1	**SFA1 < 600 µm**	**SFA1 < 63 µm**	**SFA2 < 600 µm**	**SFA2 < 600 µm 120 mins BM**	**SFA4 < 600 µm**	**SFA4 < 600 µm 500°C 60 mins**
Physical and LOI							
Fineness[5]	53.8	52.7	8.5	36.0	0.8	40.5	31.9
d_{50}[6], µm	31.2	31.5	25.3	37.3	5.0	30.0	25.4
LOI	9.7	9.8	8.9	9.2	9.7	16.3	11.8
Chemical Composition							
CaO	4.4	5.1	5.0	2.5	2.6	2.0	1.9
SiO_2	44.3	42.7	46.4	47.0	49.4	42.9	44.9
Al_2O_3	21.8	20.9	23.0	25.0	24.8	23.3	24.4
Fe_2O_3	9.0	8.8	9.3	8.6	9.4	7.6	8.0
K_2O	2.0	2.0	2.3	2.5	2.5	2.1	2.1
Na_2O	0.8	0.9	0.8	0.9	0.9	1.0	0.7
SO_3	1.6	1.9	1.6	1.0	1.3	1.0	0.9

[1] < 600 µm, < 63 µm passed through sieve size indicated (finer fraction tested)
[2] Passed through sieve size indicated and balled milled (BM) for 120 minutes
[3] Passed through sieve size indicated and heat treated for 60 minutes at 500°C
[4] Percent unless noted otherwise
[5] Percent retained on a 45 µm sieve (Dry fly ash tested to BS EN 450-1, wet fly ash - mean of 6 tests)
[6] Median particle size

The results from tests for water requirement are given in Figure 4 and indicate that stockpile fly ashes gave values between 102 and 109% with corresponding median particle sizes > 25 µm.

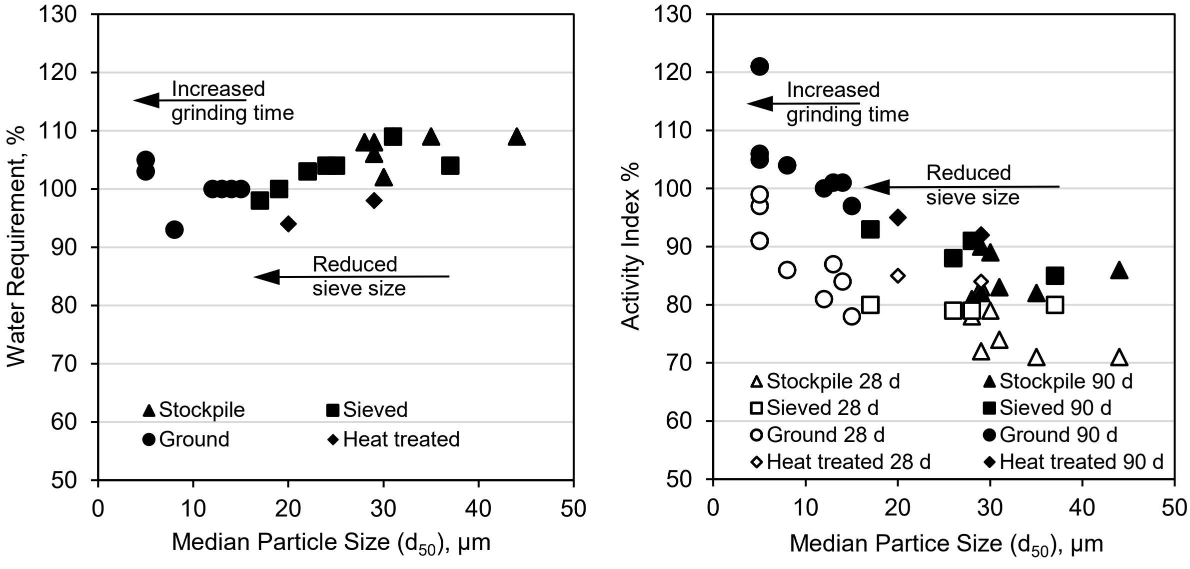

Figure 4. Effect of median particle size on water requirement and activity index of selective stockpile and processed fly ashes

Sieving gave gradual reductions in water requirement with median particle size, which were greatest with the finer sieve (63 µm). These highlight the benefits of removing coarse particles, agglomerates and carbon, although other effects noted in Figure 2, e.g., small agglomerates and products on particle surfaces, are still likely to be present.

Grinding fly ash for a short period of time (20 minutes) gave reductions in water requirement. Increased grinding periods (60 minutes) lead to further reductions, however, extending this (120 minutes) lead to increased water requirements. The changes occurring suggest that initially the process breaks down agglomerate structures, giving benefits to water requirement. However, as the period is extended, fly ash particles may begin to fracture, increasing the surface area, with the reverse then occurring.

Heat treatment of the two fly ashes in these tests gave reduced LOI by 1.0 and 1.6% (with both having values < 5.0%) and similar/lower particle sizes compared to the initial materials, leading to benefits in water requirement. As noted in Table 2 (for SFA4) greater reductions in LOI were found when this was initially higher, and it is possible that more significant effects could be achieved with increased temperature/exposure time. The different behaviour noted for median particle size and water requirement between materials in Figure 4 corresponds to the particle characteristics associated with the processing used. Most were effective in reducing water requirement, with ground and heat-treated fly ashes having values below 95%.

The results from the activity index tests, also shown in Figure 4, demonstrate that most of the stockpile fly ashes were below the 75 and 85% limits at 28 and 90 days in BS EN 450-1. By sieving at 600 µm and 63 µm, there were small changes in activity index with values above the Standard limits achieved. This was also noted by grinding with greatest effects corresponding to the reductions in particle size with extended periods. Similarly, heat treatment gave small increases in Activity Index compared to those of the original material.

Concrete Properties

SP doses in concrete to achieve a target slump of S3 and cube strength for selected processed stockpile fly ashes are shown in Figure 5. In this case, for (i) only coarse sieving (600 µm) was considered, with effects similar to the water requirement tests, with small differences in SP dose requirement noted after carrying this out. The ground fly ash also gave reductions in SP requirements, corresponding to agglomerate breakdown in the material. However, in this case, unlike water requirement, increases were not obtained as the period was extended, although this has been noted in other tests [10].

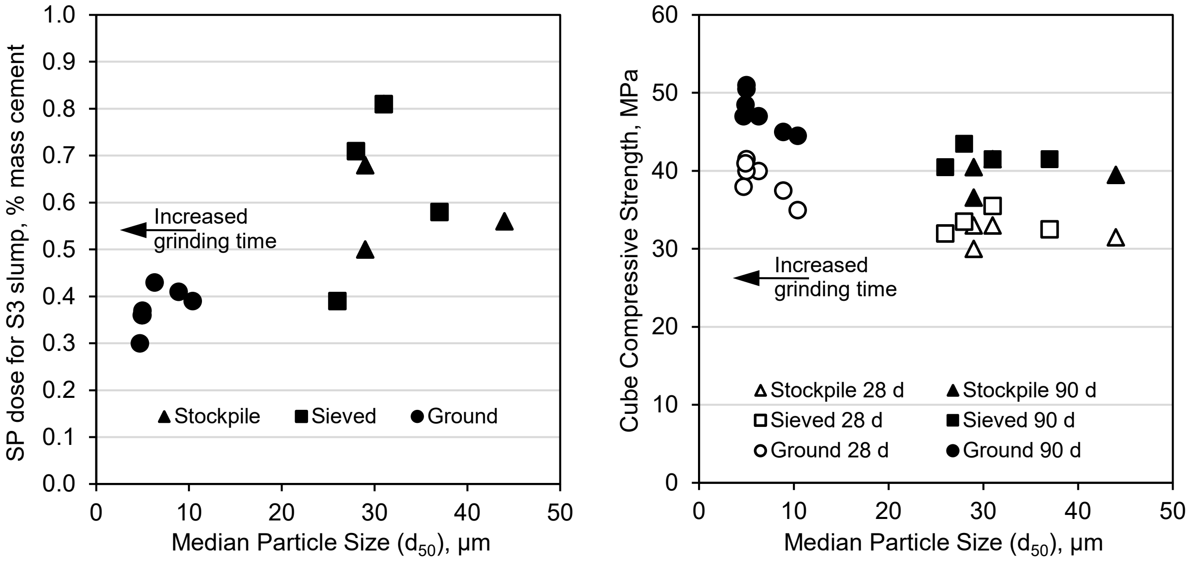

Figure 5. Relationships between median particle size, superplasticizer dose and cube strength of selective stockpile and processed fly ash concretes (30% fly ash in cement, w/c = 0.53)

The 28 and 90 day cube strengths for selected stockpile fly ash concretes are also shown in Figure 5. With sieving, there were small differences in cube strength, much like the Activity Index tests in Figure 4. More noticeable effects were found with increased grinding periods and reductions in median particle size with similar behaviour between the two test ages and increases of 8.0/8.5 to 8.0/11.0 MPa obtained respectively (following 120 minutes grinding) compared to the stockpile materials, again generally agreeing with Figure 4.

4 Processing at larger scale

To verify the laboratory studies, processing trials at increased (pilot/benchtop) scale were carried out on a stockpile fly ash. Following recovery from the stockpile, the material (SFA8) was dried through exposure to a hot air stream and de-agglomerated (pin mill, PFA2), and then either air classified (PFA3 – finer fraction tested) or micronized (spiral jet-mill, PFA4). For PFA2 and PFA4, carbon removal (low carbon (LC)), by triboelectric separation was also carried out.

A summary of the results is shown in Figure 6, which indicates that the median particle size of the fly ash changed little with drying and de-agglomeration, much like sieving at 600 µm in the laboratory. This reduced progressively with air classifying and micronizing, similar to 63 µm sieving and grinding in the laboratory, respectively. Reductions in median particle size were also noted with carbon removal for PFA2(LC), which is similar to some of the heat-treated materials in the laboratory, with small increases with PFA4(LC), which may relate to its high fineness which can affect fly ash/carbon separation [11].

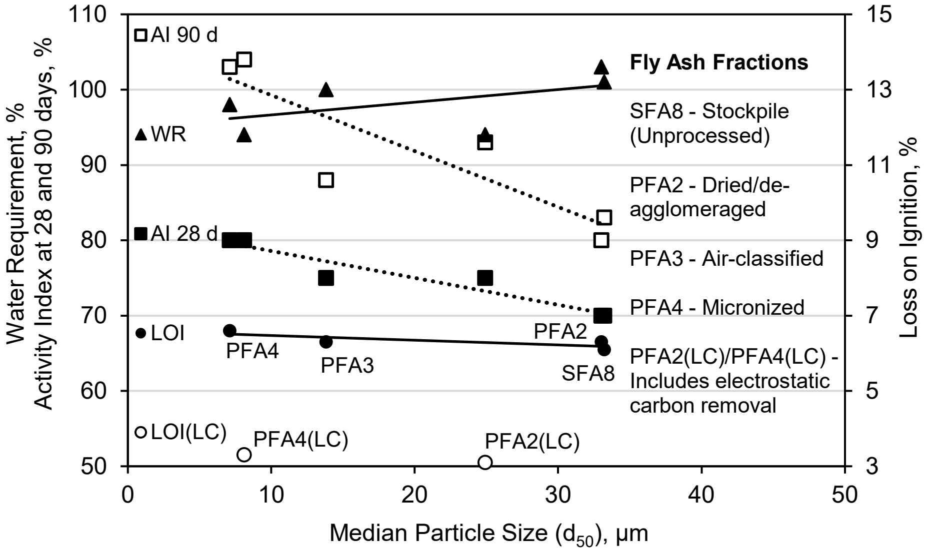

Figure 6. Comparison of median particle size and various properties of fly ash processed at larger scale

The LOI gave little change except for PFA4, which increased slightly and could reflect the opening of particle surfaces during processing, as mentioned earlier. As expected, reductions in LOI were obtained by electrostatic carbon removal. Water requirement (WR) was also lower with processing and followed particle size, with finer material and that treated by carbon removal around the BS EN 450-1 limit (95%). Activity index (AI) values below the Standard limits were obtained for the stockpile and dried/de-agglomerated material, but passed the test following processing, with greater effects as the particle size reduced.

Tests on concretes of the same mix proportions (equal w/c ratio) and target slump as above (not shown), indicate that SP dose requirements tended to reduce with fly ash median particle size. There was little effect on 28 and 90 day concrete strengths for PFA2 and 3 compared to SFA8 and slight increases for PFA4 following micronizing (of about 2.0 to 3.0 MPa) [9]. Given the water requirement results, concrete mixes at equal SP dose and with water savings (different w/c ratio), demonstrate it is possible to obtain further benefits by this means [12].

5 CONCLUDING REMARKS

The article has shown the changes taking place when fly ash is stored wet and the typical characteristics of material held under these conditions, as well as its effects on concrete. It also demonstrated that processing by various means at both laboratory and larger scales can be effective in achieving properties which meet the requirements of the BS EN 450-1 Standard, whilst giving benefits to concrete properties. The results suggest the approach followed could offer a potential route for sourcing material in future, although identifying recovery/processing strategies for particular stockpile materials and end uses will be important. Energy use associated with the processing techniques and the wider range of concrete properties, including durability, are other aspects requiring consideration.

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