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Experiences of Processing Fly Ashes Recovered from United Kingdom Stockpiles and Lagoons, their Characteristics and Potential End Uses

M Roderick Jones[1], Michael J McCarthy[1], Li Zheng[1], Thomas L. Robl[2] and Jack Groppo[2]

[1]University of Dundee, Concrete Technology Unit, Dundee DD1 4HN Scotland,
[2]University of Kentucky, Center for Applied Energy Research, 2540 Research Park Drive, Lexington, KY 40511.

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ABSTRACT

Engineers and specifiers have a responsibility to protect the environment from which raw materials for construction products are drawn. Perhaps the most pressing of these, no matter individual viewpoints, is minimising embodied CO_2, given the generally agreed contribution it makes to climate change. Furthermore, there needs to be less waste and a reduced dependency on primary aggregates. For this reason worldwide, there is a renewed desire to exploit fly ash resources ‘locked up’ in long-term storage, which in the United Kingdom alone equates to more than 100 million tonnes.

This paper summarises a two-year UK/US research project that investigated the effectiveness of recovering and processing lagoon and stockpile fly ashes from UK long-term storage sites and their complete utilisation in a range of applications. The main aim was to reduce size and/or compositional heterogeneity of the raw feed by splitting and, thereby, concentrating the material into size ranges, which enable utilisation in a wide range of added value applications. These ashes were produced under low emission conditions and presented significant challenges to processing. These were addressed by combining primary separation, column and mechanical froth flotation and lamella hydraulic classification.

The characteristics of the processed ash fractions are described, including material yield details. The performance of these in a number of matched end uses are reported, including as a cement/sand component in normal, precast and foamed concrete, highway construction and clay brick manufacture. The calorific value of separated carbon particles was measured to investigate their potential as a co-fuel for reburning or in Portland cement manufacture.

INTRODUCTION AND BACKGROUND

Engineers and specifiers have a responsibility to protect the environment from which the raw materials for construction products are drawn. Perhaps the most pressing of these, no matter individual viewpoints, is minimising embodied CO_2, given the generally agreed contribution it makes to climate change. It seems incongruous then, that while many countries fully utilise furnace bottom ash, the use of fly ash often remains below 50% of that produced annually and much, therefore, goes to long-term storage, which in the United Kingdom is more than 100 million tonnes.[1] The reasons for this are both historical and commercial, including perhaps a lack of year round availability, but whatever the causes there must be a change in attitude by all of those involved to protect the environment in a responsible and economic manner.

Although a much more disparate industry, with a primary focus on electricity production rather than ash utilisation, the success of slag and silica fume materials producers must be noted. Both materials are widely seen as adding significantly to concrete performance and indeed demand exceeds production. The question must be asked whether there are any concrete mixes that could not be beneficially improved by the use of fly ash. Most would agree that there are very few applications when it does not enhance performance. If this is so, then why over the past two decades has the situation not changed?

The hand of the regulator and the tax man is, however, changing this and quite quickly. With the effects of Carbon Trading beginning to be felt worldwide many cement producers are looking at fly ash and slag as a way of achieving cement production volumes, while reducing clinker consumption. It seems likely that over the next decade there will be few ‘pure’ Portland cements being produced and the vast majority of concrete will use a factory-blended composite cement or a mixer blend. It is, therefore, important that the fly ash industry is able to respond to this demand.

Fly ash is highly heterogeneous and recovering it from long-term storage, for use in the construction and materials industries, means that processing will be necessary. The traditional uses of fly ash, in particular the higher value and volume outlets, are cement, grout and fill and to make best use of the available material it makes sense for it to be separated to specific fractions. This project was conceived to look at the scope of using all of the phases found in fly ash from cenospheres to the unburnt coal/residual carbon.

This paper summarises a two-year UK/US research project that utilised pilot plant combining primary separation, column and mechanical froth flotation and lamella hydraulic classification, that could economically process lagoon and stockpile fly ashes from UK long-term storage sites. These fly ashes were produced under low emission conditions and presented significant challenges to processing.

The main aim was to reduce size and/or compositional heterogeneity of the raw feed by splitting and, thereby, concentrating the material into size ranges, which enable utilisation in a wide-range of added value applications.

RESEARCH PROGRAMME

The research comprised four main stages: (i) commissioning the pilot processing system, (ii) sampling and characterising materials from power station sites, (iii) examining the materials produced following processing, and (iv) carrying out scoping studies covering a range of applications of low, medium and high value with the processed material.

The processing system used in this investigation was developed by the CAER at the University of Kentucky, which has proven to be effective in processing fly ash in the USA.[2, 3]

Five different power station sites were investigated and material samples from these characterised. The investigated sites covered lagoons and stockpiles, such that these types of storage and their effects could be quantified.

One of the stockpile materials was selected for bulk processing to produce sufficient quantities for use in various applications. The focus of this work was to examine the use of the various separated materials, ranging from filler to coarse sand to cement component. In addition, the high carbon content material was examined as a potential co-combustion fuel.

OVERVIEW OF PROCESSING SYSTEM

The system included (1) pre-screening, (2) slurrification, (3) primary classification, (4a) column / (4b) mechanical froth flotation, and (5) lamella hydraulic classification. The general arrangement of the processing system is shown in Figure 1.

Pre-screening (Figure 2a) prevented very coarse particles, vegetation, etc from entering the system. The material was then thoroughly mixed in a slurrification tank (Figure 2b), and agitated continuously in the tank during processing to keep it well mixed and stable. Primary classification (Figure 2c) was used to remove coarse (i.e. generally >150μm) particles and to reduce the carbon content.

Column (Figure 2d) or mechanical (Figure 2e) froth flotation was used to remove carbon. These differ in terms of their effectiveness in removing fine and coarse carbon. During column flotation, bubble generation is achieved with an internal sparger at the pipe base, made from perforated rubber, and compressed air. Feed slurry enters the column at about two-thirds of its height and descends against a rising swarm of bubbles. These collect floatable particles (i.e. carbon) and carry them to the overflow where they are removed as froth. The lower carbon content material is collected as tails. Mechanical flotation used a pilot-scale bank of two cells. During processing, the slurry is mechanically agitated by an impeller. It was considered that the high shearing force of this would be beneficial in separating carbon from fly ash particles and hence in the achievement of low carbon tails.

The bubbles, generated by self-aeration from the impeller are distributed to the slurry through the diffuser and collect floatable particles, taking them to the cell surface where they form a stable froth and are removed by scrapers. The lower carbon content slurry is fed into the next cell or collected as tails through a weir.

Lamella hydraulic classification (Figure 2f) was used to separate recovered material into different size fractions. Five fractions were obtained from the classifier, i.e. (i) coarse fraction, U1; (ii) medium fraction, U2; (iii) fine fraction, U3 and U4 (iv) ultrafine fraction, UF (i.e. U5) and (v) cenospheres.

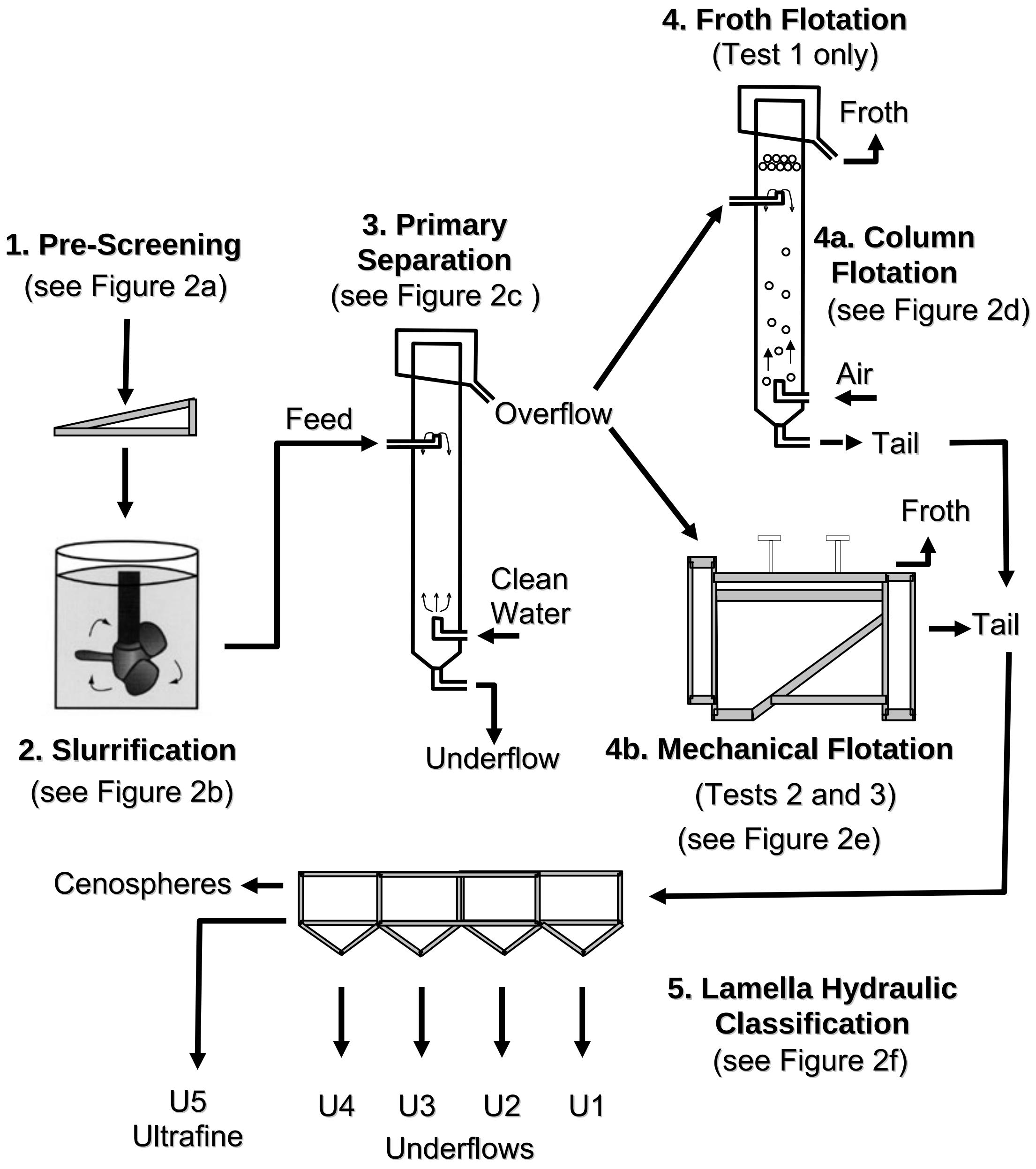
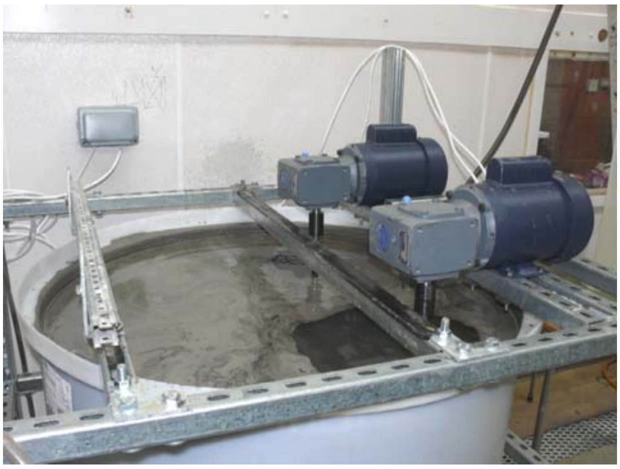


Figure 1. Overview of CAER pilot processing plant.

(a) Pre-screening



(b) Slurrification

(c) Primary classification

(e) Mechanical froth flotation (bank of two cells)

(d) Column froth flotation (same equipment as shown in (c) however, compressed air input used as shown in the photograph)

(f) Lamella hydraulic classification

Figure 2. Components of CAER pilot processing plant.

SAMPLING AND CHARACTERISATION OF RAW FLY ASH

The main purpose of examining material in storage areas at power stations was to determine property variations within these areas, and to establish requirements with regard to processing. Five different power station sites were investigated and material samples from these characterised.

There were two main lagoons at Power Station 1, each with a storage capacity of 400,000 tonnes. In total, 39 samples were taken.

At Power Station 2, there was a 1 Mt stockpile. All material at the site was conditioned and has been produced in the last few years. Only a single large sample of about 3.5 tonnes was taken from the stockpile.

At Power Station 3, all of the material was conditioned and then stockpiled. The stockpile area, a large mound, was about 50 hectares, and its height around 50 metres. Estimated quantities of conditioned fly ash at the site were over 16 Mt. In total, 51 samples were taken.

Material from Power Stations 4 and 5 was deposited at the same storage site, following slurrification and pumping. However, that from Power Station 4 was dewatered and then stockpiled, while that from Power Station 5 was stored in lagoons. Six samples from each power station were taken for characterisation.

The results from the tests are given in Table 1. These indicate that material from Power Station 3 was finer but had higher loss-on-ignition (LOI) than that from Power Station 1. Based on the characterisation results of the samples from the five power station sites investigated, it can be seen that the majority of lagoon and stockpile materials have high LOI (>10%) and are coarse (45μm sieve retention >40%).

This means that the materials do not conform to standards for use as a cement. Processing to separate them into various fractions suitable for the full range of possible end uses is therefore necessary.

In addition, it was found that the LOI tended to increase in more recently produced material at most of the sites, suggesting that this has higher carbon contents. This may be due to changes in burning conditions, e.g. lower temperature to meet NO_x emission limits.[4]

In stockpiles, the material fineness and its variation with location tended to be lower than that in lagoons. In addition, significant quantities of cenospheres were found in stockpile material (note: cenospheres are normally extracted from lagoons due to there very high net worth).

Table 1. Characteristics of raw fly ashes recovered from United Kingdom stockpiles and lagoons.

		Power Station Site				
		1	2	3	4	5
Storage Type		Lagoon	Stockpile	Stockpile	Lagoon/ stockpile	Lagoon
Number of Samples		39	1	51	6	6
Physical Properties						
Fineness, 45µm sieve retention, %		12 – 62	–	31 – 42	24 – 55	28 – 46
	mean	40	53	37	41	34
Particle Size Distribution, µm	D_{10}	3 – 14	12	4 – 7	3 – 5	2 – 4
	D_{50}	13 – 100	55	27 – 44	29 – 38	28 – 35
	D_{90}	50 – 500	165	97 – 155	119 – 273	115 – 135
Loss on Ignition, %		4 – 21	–	11 – 18	11 – 18	13 – 16
	mean	8	10	14	14	14
Bulk Oxide Composition, % by mass						
CaO		2 – 6	–	1 – 3	5 – 7	5 – 6
	mean	3	5	2	6	6
SiO_2		40 – 60	–	36 – 46	38 – 45	37 – 45
	mean	47	42	40	42	42
Al_2O_3		23 – 33	–	19 – 24	19 – 23	19 – 23
	mean	28	26	21	21	20
Fe_2O_3		3 – 8	–	5 – 9	5 – 7	5 – 7
	mean	5	9	7	6	6
Major Phase Composition, % by mass						
Quartz		3 – 14	–	2 – 6	7 – 9	7 – 8
	mean	8	5	4	8	7
Mullite		14 – 32	–	5 – 10	10 – 16	10 – 16
	mean	22	13	7	13	12
Amorphous material		47 – 72	–	61 – 76	56 – 66	58 – 66
	mean	59	69	67	61	63

CARBON/FLY ASH SEPARATION TESTS (Release Analysis)

Release analysis was carried out with samples from the five sites. This is an initial laboratory mechanical froth flotation test using a small quantity of representative sample of approximately 200g. This test indicates the limits of carbon removal that can be achieved by froth flotation. Before the test, particles >150µm were removed by sieving to simulate the effect of primary classification. The results of the tests are compared in Figure 3. It can be seen that Power Station 4 fly ash was the most amenable to LOI reduction by flotation (i.e. at the same froth/tails ratio, lowest LOI of tails can be achieved), followed by Power Station 3 fly ash. It was not clear from this work why this was the case but visually these ashes had the least agglomeration in the raw state. Carbon/fly ash separation for Power Station 1 was difficult, as the results show the lowest tails fraction was obtained for the same LOI level in the five materials. For example, to obtain tails with LOI <6%, nearly 40% material was removed in the froth for Power Station 1 fly ash, while this was only about 15% for that of Power Station 4.

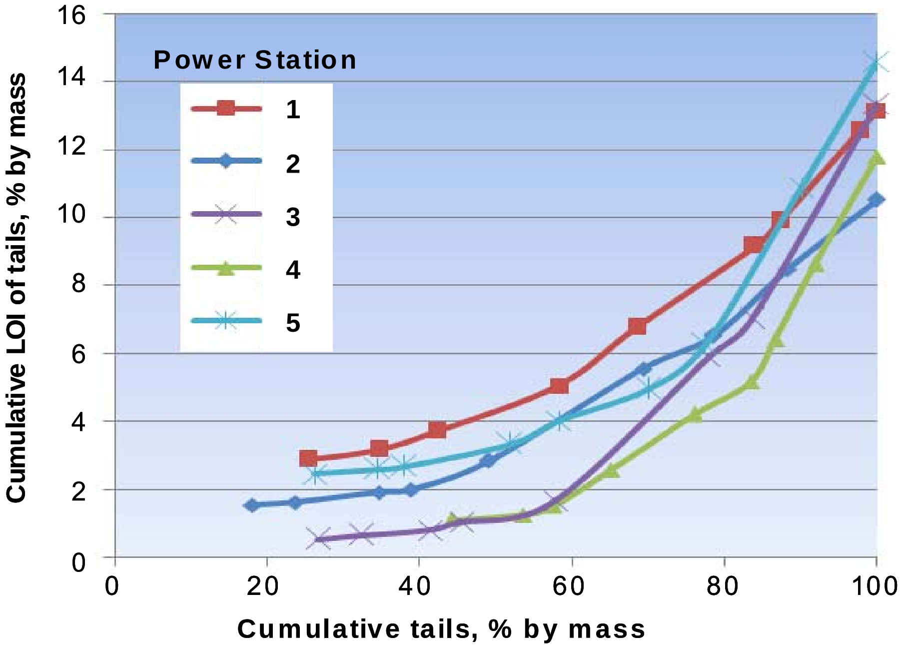


Figure 3. Release analyses for tails of the 5 fly ash samples (<150 µm fraction).

TESTS TO DETERMINE OPTIMUM PROCESSING (Pilot-Scale Processing)

Given the results from the release analyses, pilot-scale processing tests using Power Station 3 fly ash were carried out. Three tests, using different combinations of processing components, were carried out to determine the potential of different techniques for separating carbon and fly ash particles from this material, as follows:

Test 1: Column froth flotation and lamella hydraulic classification (Figure 4).

Test 2: As Test 1 plus primary classification and mechanical flotation was used instead of column flotation (Figure 5).

Test 3: As Test 2, with mechanical flotation run twice (Figure 6).

The processed fractions resulting included underflow in primary classification, froth from flotation, four different sized underflows (denoted U1, U2, U3, and U4) and the ultrafine lamella overflow (U5). Any cenospheres were captured in the lamella. The fineness and LOI values of various processed fractions for the three tests are given in the flowcharts (Figures 4 to 6) and are discussed in the following sections.

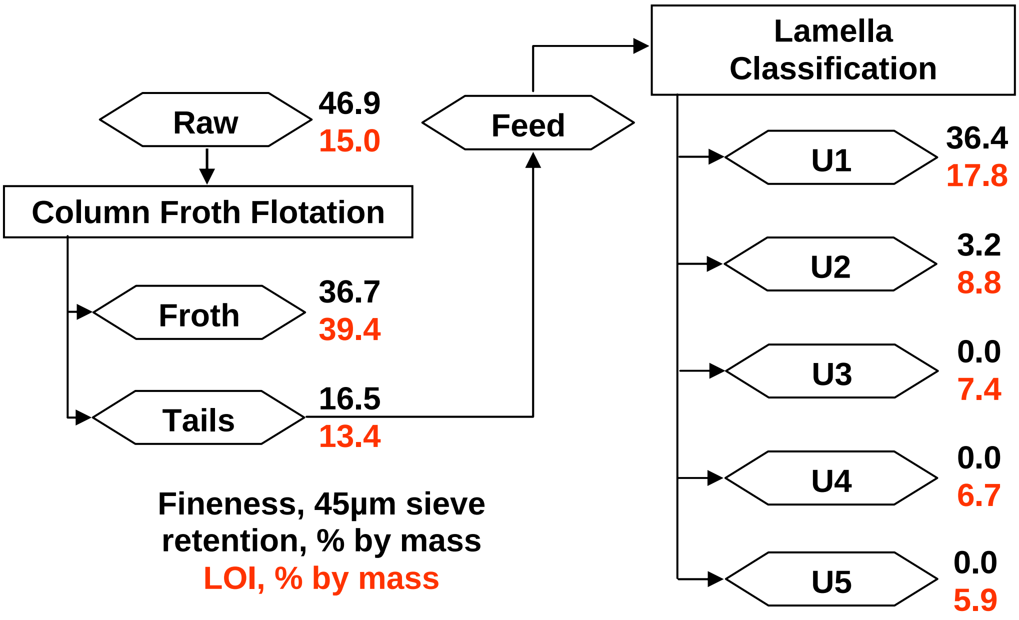


Figure 4. Test 1: Processing with column flotation and lamella classification.

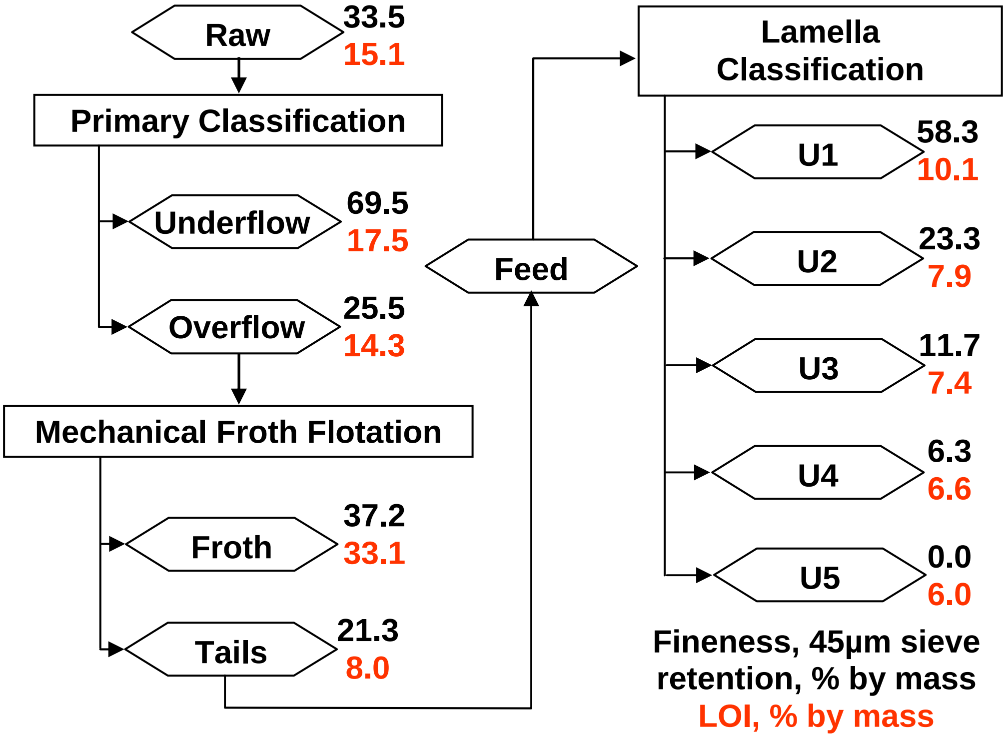


Figure 5. Test 2: Processing with primary classification, mechanical flotation and lamella classification.

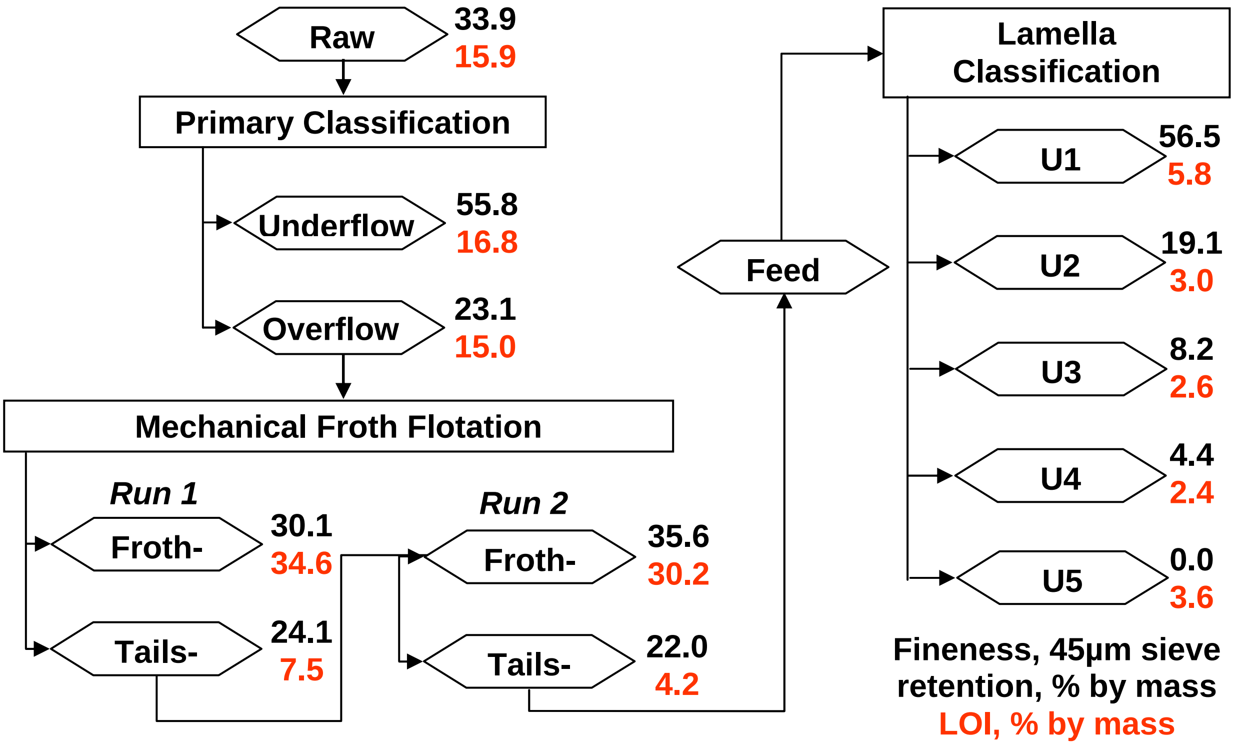


Figure 6. Test 3: Processing with primary classification, two runs of mechanical flotation and lamella classification.

Fineness (45µm Sieve Residue)

Primary classification was used in Tests 2 and 3. As shown in Figure 5 and Figure 6, the fineness of the overflow was reduced from 34% to around 23% to 25% following this process.

In froth flotation, as shown in Figures 4 to 6, the fineness range of the froth particles was 30% to 37%, while that of the tail particles was 17% to 24%. The tail particles of Tests 2 and 3 were coarser than those of Test 1, as a portion of fine particles was 'lost' during primary classification, which was not used in Test 1, and it was also found that mechanical flotation took more fine particles to the froth.

The feed was separated into different sized fractions, U1 to U4 using lamella classification and ultrafine overflow, U5. As shown in Figures 4 to 6, since the feed particles of Test 1 were finer than that of Tests 2 and 3, the corresponding lamella classification outputs were also finer. However, their relative fineness was similar.

Figure 7 shows the particle size distribution of the feed and separated fly ashes of lamella classification from Tests 1 and 3. Both indicate progressively finer material was produced from U1 to U5. U2 to U5 of Test 1 and U3 to U5 of Tests 2 and 3 met the BS EN 450-1 Category S fineness requirement. The overflow, U5, with a mean particle size around 5µm is likely to contain the most pozzolanically reactive phases.[5]

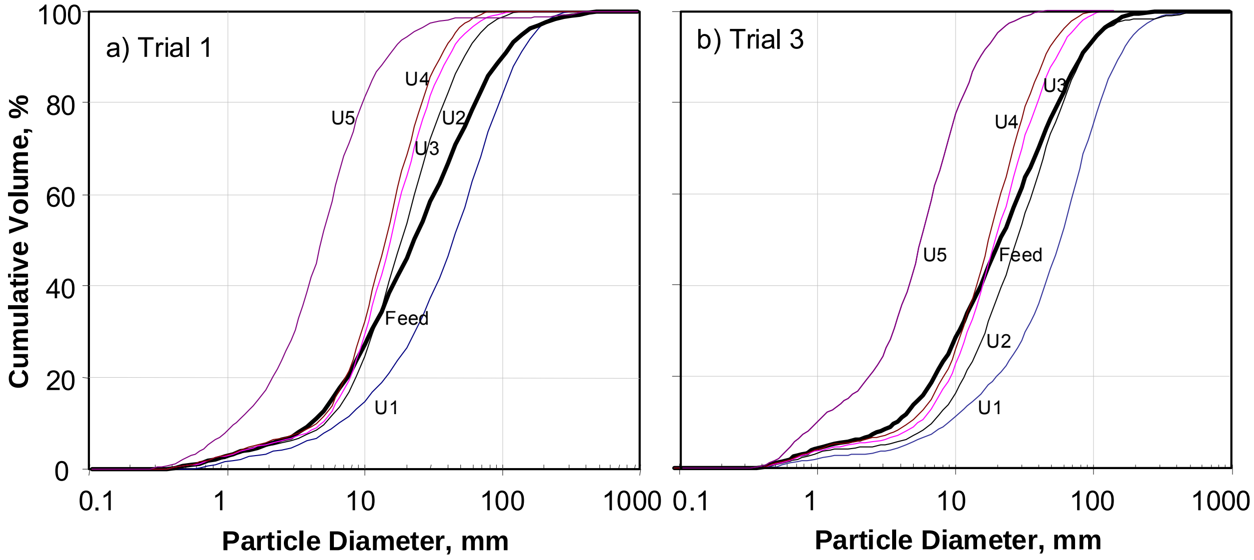


Figure 7. Particle size distribution of the feed and separated fly ashes from lamella classification.

Loss-on-Ignition (950^{o}C)

The LOI results are also given in the flowcharts (Figures 4 to 6). The primary classification reduced the LOI by about 1% before froth flotation.

With froth flotation, the LOI results from the three processing tests were different. Test 1 used column flotation without primary classification. The LOI of the froth was approximately 40%, while the LOI of the tails was around 13%.

The LOI results of the froth and tails from Test 2 and the first run of mechanical flotation in Test 3 were similar, i.e. froth 33 to 35% and tails 7.5 to 8%.

The second run of mechanical flotation (Test 3) further reduced the LOI of the tails to about 4%. These suggest that column flotation was effective for obtaining high carbon froth and mechanical flotation low carbon tails. The LOIs of the tails, i.e. the feeds for the following lamella classification were about 13%, 8% and 4% for Tests 1, 2 and 3 respectively.

In lamella classification, the LOI was found to gradually reduce from U1 to U5. This is because carbon particles are usually coarser than fly ash particles. It can also be seen that the LOI of U1 was higher than the feed, while U2 to U5 were lower. In Test 1, a high LOI was measured in U1, since no primary separation was used. However, the LOI of U2 to U5 was quite similar to that of corresponding fractions in Test 2. According to BS EN 450-1, the fractions U4 and U5 of Tests 1 and 2 meet the Category B LOI requirement. With the intensive carbon removal processing in Test 3, fractions, U2 to U5 met the Category A LOI requirement, and U1 that of Category B.

Particle Morphology

SEM micrographs were taken for all of the feed and processed materials for each processing test. Figure 8 illustrates the effect of processing on the particle sizes and shapes in Test 3.

Figure 8(a) to (g) compares the particle shapes of feed, primary classification and flotation materials. It can be seen that the overflow was finer than the underflow from primary classification. The tails of flotation were also finer than the froths from the flotation processes.

Figure 8(h) to (l) show the particle sizes of underflows, U1 to U5, from lamella classification. It can be seen that the particle size and shape changed for different fractions, from the coarsest U1 to the finest U5. Agglomeration of particles was noted in some fractions and hydration products were also present on particle surfaces.

Figure 8(m) and (n) illustrates the ultrafine fraction, U5, at different magnifications and show some reaction products were present on these particles.

Material Yields

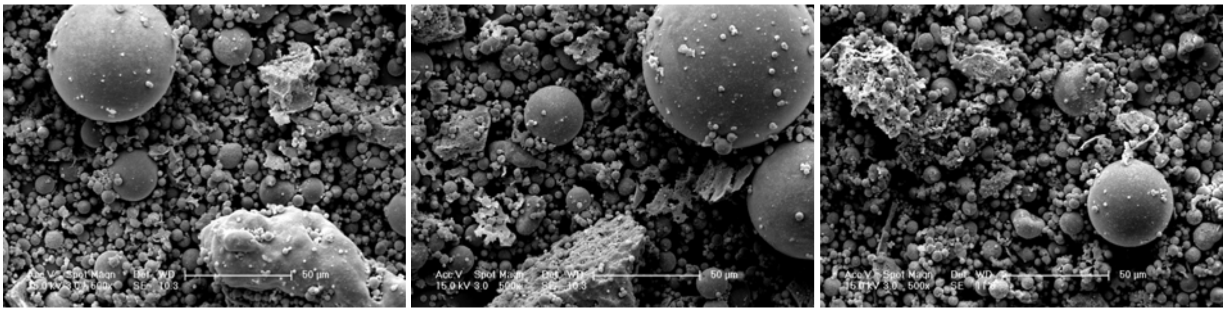
The material yields of the three tests are given in Table 2. The calculation is based on mass balances of the feed and output at each processing stage. In this work, the key factors were LOI and sub 5μm particle content, as carbon removal also resulted in loss of ultrafine material.

The mass balance gives the distribution of the particle phases at each stage of processing. In Test 1, there was no primary classification and the column froth flotation removed 14% of the total material, which contained 33% carbon and 9% ultrafine particles. Lamella classification removed 43% of the total material to U1, which contained 47% carbon and 28% ultrafine particles. These data indicate that a large proportion of carbon is in the coarse particle size range but the processing conditions necessary to remove these also result in the loss of a proportion of ultrafine particles.

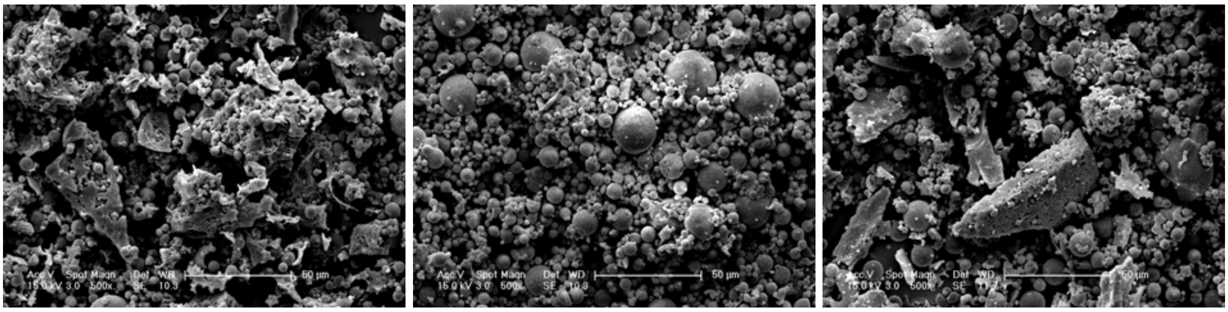
In Tests 2 and 3, primary classification was used and removed coarse carbon particles before froth flotation. In total 20-25% of the raw feed was removed and 26-27% carbon and 14-19% ultrafine particles. Test 3 removed slightly more carbon but resulted in a greater loss of fine particles.

In mechanical froth flotation, Test 2 removed 23% of the total material to the froth containing 46% carbon and 20% ultrafine particles, compared to 30%, 60% and 29% respectively for Test 3.

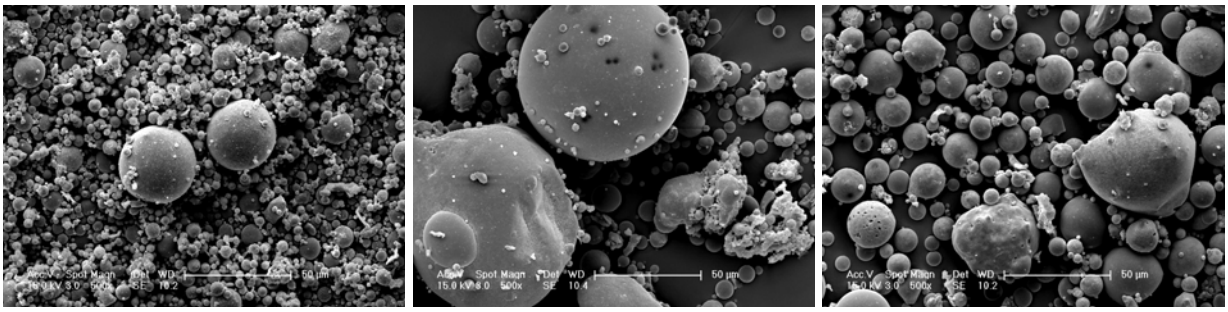
In the processes before lamella classification, Test 2 had removed 72% carbon with 44% of the total material and 34% of the ultrafine particles lost. In comparison, Test 3 had removed 88% carbon with 55% of the total material and 48% of the ultrafine particles lost. Both of these had less carbon but lost more fine particles in comparison with Test 1.



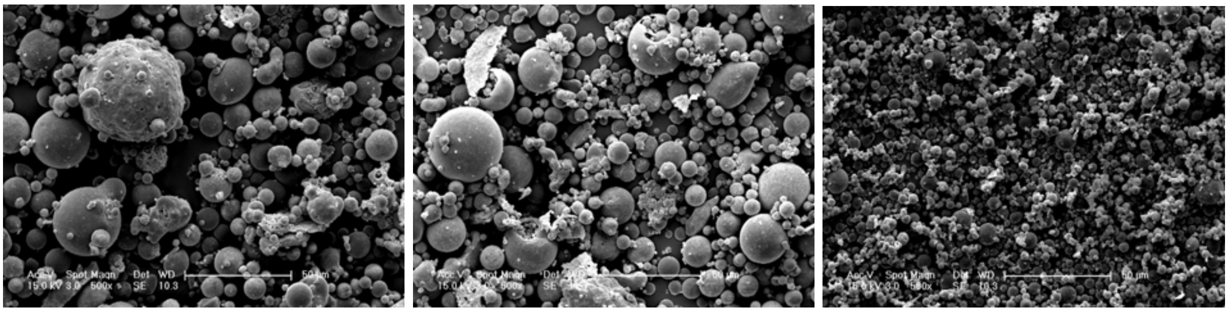
(a) Raw Feed (b) Underflow (c) Overflow



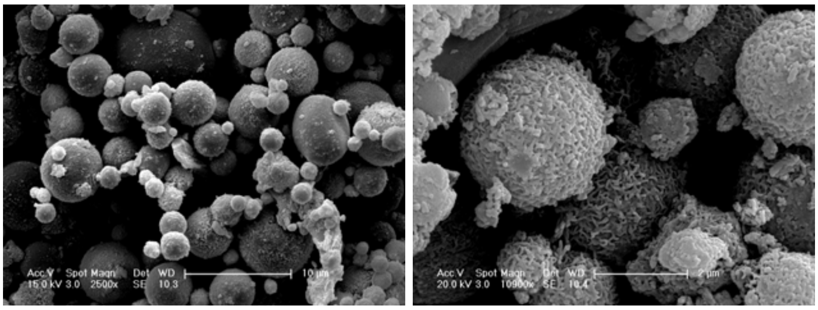
(d) Froth-1 (e) Tails-1 (f) Froth-2



(g) Tails-2 (h) U1 (i) U2



(j) U3 (k) U4 (l) U5



(m) U5 (n) U5

Figure 8. SEM micrographs of Power Station 3 feed and processed materials from Test 3 (a to i: 50μm scale bars, m: 10μm and n: 2μm scale bars)

Table 2. Mass balance of the material in processing.

Ash	Mass, %								
	Total mass			Carbon			<5 µm particles		
	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3
Raw Feed	100	100	100	100	100	100	100	100	100
Primary Classification									
Underflow	-*	20.3	24.9	-	25.9	27.4	-	13.6	18.7
Overflow	-	79.7	75.1	-	74.1	72.6	-	86.4	81.3
Froth Flotation of Overflow									
Froth-1	13.6	23.4	23.1	32.9	46.4	48.9	9.1	20.0	21.5
Tails-1	86.4	56.3	52.0	67.1	27.7	23.7	90.9	66.4	59.8
Froth-2	-	-	6.6	-	-	11.7	-	-	7.7
Tails-2	-	-	45.4	-	-	12.0	-	-	52.1
Lamella Classification of Tails									
U1	43.3	17.7	14.0	47.1	11.1	5.7	28.0	8.2	8.1
U2	17.4	12.0	10.5	9.5	5.9	2.3	14.4	8.4	7.8
U3	10.4	10.2	8.7	4.7	4.7	1.6	9.3	8.6	8.2
U4	8.0	9.2	8.1	3.2	3.7	1.4	7.7	8.0	9.0
U5	7.3	6.2	4.1	2.6	2.3	1.0	31.5	33.2	19.0

* See Figures 4 to 6 for the processed materials.

In Test 1, 7% U5 was obtained compared with 6% in Test 2 and 4% in Test 3. However, in Test 1 the total of U3, U4 and U5, ie that classified as a cement in BS EN 450 was similar to that of Test 2. Test 3 obtained less cementitious materials but had a lower LOI.

On the basis of these calculations, it was decided, given the focus in this work on carbon removal, to adopt the Test 3 combination of processing methodologies to provide bulk material for the end use scoping studies.

END USE SCOPING STUDIES

A wide range of end uses for the processed materials was studies with the aim of full utilisation. There is a long history of exploiting fly ash in various applications[6-8], mostly in the construction industry.[9] Indeed, comprehensive research of fly ash in different areas has been carried out by the Concrete Technology Unit.[1, 6-8, 10-11]

The processed fly ashes were tested as follows:

- U3+U4+U5: cement in concrete.
- U1 and U2: foamed concrete filler and normal concrete active sand.
- U1 and U4: lime -soil stabilisation.
- U2 and U4: clay replacement in fired bricks.
- Underflow of primary classification and froth: potential as a fuel.

Fly Ash in Concrete

Fly ash used as a cement in concrete covers a wide range of applications, which have been extensively studied at Concrete Technology Unit.[12-20] In general, the fine fraction of fly ash can be used as cementitious material in factory blended cement or in mixer blended concrete. The coarse fraction can be used as filler or active sand. The benefits of using fly ash in these high value applications are well established for run-of-station material and include improved fresh concrete properties, reduced heat of hydration, long-term strength development and enhanced durability.[21-23] This part of the research determined whether processed fly ash gave a similar level of benefit.

Standard mortar tests

Water requirement and strength activity index of standard mortars (0.5 w/c ratio with standard sand) according to BS EN 450-1, which are normally used to assess the performance of fly ash (combined with Portland cement, PC, 42.5N) with regard to its use in concrete, were measured for Test 3 processed material and the results are given in Table 3.

These show that the water requirement of the processed material mortars was significantly reduced compared to that of the raw (unprocessed) material. Fractions U2 to U5 met the requirement of BS EN 450-1 Category S fly ash (≤95%), and suggest that water savings could be achieved in using the materials in concrete.

The activity index of the processed materials increased with fineness. Fractions U3 to U5 met the requirement of BS EN 450-1 (I_{28}≥75% and I_{90}≥85%). The results suggest, perhaps surprisingly, that similar activity indices were obtained between the finer processed fraction and raw material mortars.

Mixer blended concrete

Processed materials from Tests 1 and 3 were used as an addition in concrete (of w/c ratio 0.5) in laboratory tests. These contained PC, 42.5 N and raw/processed material at a level of 30%, with natural sand and gravel (20 mm maximum size). The finer fractions of the processed materials, U3/U4 blend, U4/U5 blend and U5 were used and their effect on consistence (slump) and strength development examined. The results are given in Table 4.

Table 3. Water requirement and strength activity index of processed materials.

Standard Mortar Mix	Water Requirement		Mortar Compressive Strength, N/mm²			Activity Index, %	
	ml	%	7 d	28 d	90 d	28 d	90 d
PC Ref	225	-	43.0	50.0	56.0	-	-
Raw Ash	225	100%	32.0	41.5	50.0	83	89
U1	220	98%	24.5	31.0	37.5	62	67
U2	205	91%	27.0	37.5	46.0	75	82
U3	200	89%	29.0	38.5	47.5	77	85
U4	200	89%	30.0	39.5	49.0	79	88
U5	195	87%	31.5	41.5	52.0	83	93

Table 4. Consistence (slump) and strength development of concrete made with different processed materials.

Mixer Blend Concrete Mix	Slump, mm	Cube Strength, N/mm²				f_{90}/f_{28}
		7 days	28 days	60 days	90 days	
PC Ref	50	44.0	52.0	54.0	58.0	1.12
Raw Ash	65	27.0	41.0	46.5	48.0	1.18
U3+U4* (Test 1)	75	21.5	32.0	37.0	35.5	1.12
U5 (Test 1)	145	24.5	35.5	43.0	47.0	1.32
U3+U4 (Test 3)	70	23.0	38.0	36.5	41.5	1.09
U4+U5 (Test 3)	90	24.5	37.5	33.0	47.5	1.27
U5 (Test 3)	125	22.0	36.0	44.5	48.5	1.34

* 50% by mass U3 combined with 50% by mass U4

The results indicate that the consistence (slump) of the concrete improved with the addition of processed material, especially ultrafine, U5. Concrete made with raw fly ash had similar consistence to PC concrete. Progressive improvements in consistence were noted in concrete made with processed material, U3+U4, U4+U5, and U5 compared to that with raw fly ash, which is in general agreement with the results obtained from the water requirement tests on mortar (Table 3).

The compressive strength of the concrete mixes indicates that those with processed material tended to have similar or slightly lower strength than that with raw material, although their 28/90 day strength development ratios (f_{90}/f_{28}) were similar to or higher than this (Table 4).

The results again show general agreement with the mortar tests (Table 3). These effects may be caused by surface reaction of fly ash particles during the long-term wet storage and/or processing. Indeed, reaction products were found on the surfaces of most ultrafine particles, especially in the U5 fraction (Figure 8), which may affect pozzolanic reactivity.

Precast concrete

The processed material combinations from Test 3, U3+U4 and U4+U5 were also used in a precast concrete application. The reference PC mix (comprising PC, 42.5 N and natural sand and gravel (20 mm maximum size)) was provided by the precast plant and the test concrete strength class was C32/40. Considering the processed fractions could improve the consistence and for the equivalent strength requirement, the w/c ratio (and water content) of the PC/processed material mixes was reduced to 0.42, compared to 0.49 for PC concrete.

The mixing was carried out at the precast plant and the concrete was used in a reinforced concrete staircase. The appearance of the three mixes and their consistence were similar. The concrete cube (100 mm) strength development results are given in Table 5. These indicate that all mixes with processed material achieved the target strength (i.e. 40 N/mm^2 at 28 days following standard water curing). After 90 days, the U4+U5 mix essentially matched the strength of the PC mix.

Table 5. Strength development of concrete in precast trials.

Precast Concrete Mix	Compressive Strength, N/mm²				
	3 days	7 days	28 days	90 days	f_{90}/f_{28}
PC ref	30.0	42.0	55.0	60.0	1.12
U3+U4	21.0	30.0	43.0	54.5	1.27
U4+U5	23.0	33.0	47.0	59.0	1.24

Foamed concrete

Fly ash has been successfully used in foamed concrete.[24-26] U1 and U2 from Test 3 were used to replace sand in this application. The target density of foamed concrete was 1000 kg/m^3, w/c ratio 0.5, and sand replacement 50%. With the addition of processed material, consistence of the foamed concrete (measured in terms of efflux time from a modified Marsh cone [11]) improved, compared to the raw material (Table 6), which appears to be due to their lower carbon contents (Figure 6).

The strength of foamed concrete also increased with the addition of processed fly ash fractions (Table 6). While the U2 mix achieved higher strength, U1 was lower than that with the raw material, which is potentially due to the loss of ultrafine particles. However, in replacing sand at a 50% mass level, all recovered/processed mixes achieved higher strength than the reference PC mix.

Table 6. Workability and strength development of foamed concrete.

Foamed Concrete Mix[a]	Efflux Time, Second[b]	Cube Strength, N/mm²				
		3 d	7 d	28 d	56 d	90 d
PC Ref	50	1.2	1.4	1.7	1.9	1.9
Raw Ash	25	1.4	1.7	2.8	3.2	3.4
U1	20	1.3	1.6	2.2	2.6	2.7
U2	20	1.5	1.8	3.2	3.7	3.9

[a] Fly ash was used to replace sand at 50% by mass.

[b] <60 seconds: mix is flowing and self-compacting, see Reference 11 for test details

'Active' concrete sand

Another application for processed fly ash in concrete is as a fine aggregate component but one that is reactive and can contribute to the concrete properties.

Work examining conditioned fly ash [27] of different fineness and following various periods of storage, in concrete (at sand replacement levels of up to 15%) indicates that benefits in terms of strength development are achievable. This 'active' contribution of the wet fly ash could clearly be exploited for processed materials, such as U2.

Lime-Soil Stabilisation

Controlling swelling in lime-stabilised sulfate-bearing soils using fly ash has been recently studied [28]. Two processed materials from Test 3, U1 and U4, were used at 6%, 12%, 18% and 24% addition levels in this application. A clay, with a SO_3 content of 1.0% which will potentially give volume stability problems, was combined with lime and the processed materials.

The results from swelling tests carried out at 40°C (according to BS EN 13286-49) indicate that processed material addition reduced swelling of the lime stabilised clay, as shown in Figure 9.

Strength at 120 days increased with processed material addition level. The results suggest that there may be an optimum level of addition in relation to this, which may relate to particle packing of the clay/lime/fly ash combination.

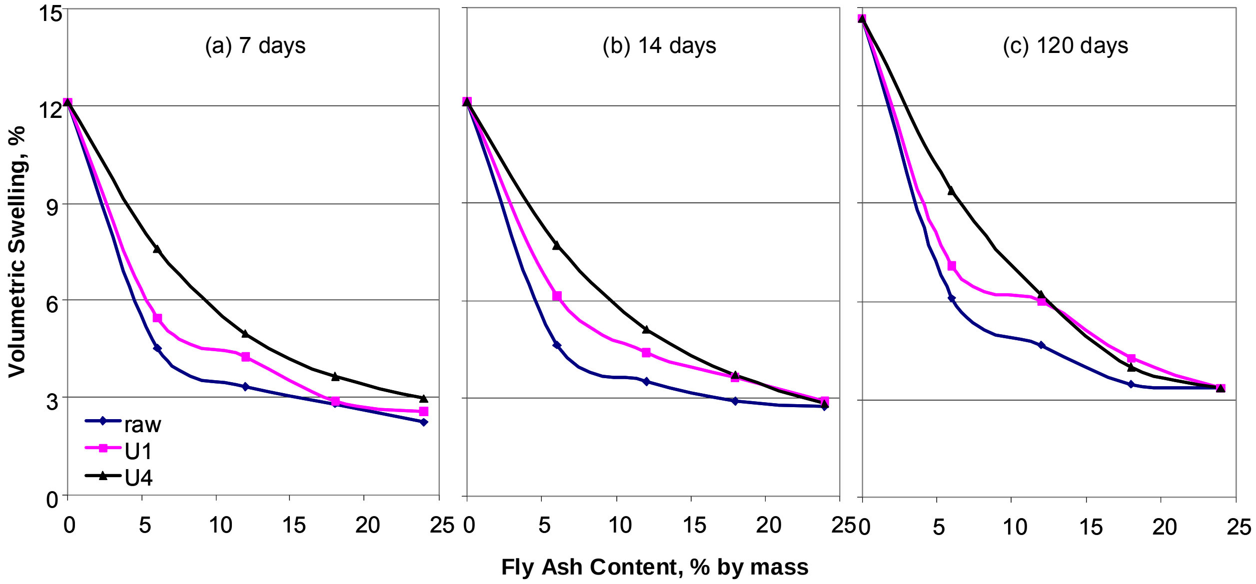


Figure 9. Volumetric swelling of the soil stabilisation test samples (in 40ºC water bath)

Clay Bricks

In this application, processed material was used to partially replace clay in fired bricks at the Ceramic Technology Group, Staffordshire University, following procedures developed by Anderson [29]. Underflow of primary classification, U2 and U4 were used as a clay replacement at levels of 10%, 20% and 30%.

Three temperatures, i.e. 1000°C, 1050°C, and 1100°C were used to fire the samples. Test results of fired bulk density, fired volume shrinkage, water absorption and tensile strength on fired samples are given in Table 7. It can be seen that the density of the clay/processed material mixtures decreased with increasing processed material content. It was also found that the lower the LOI of the processed material, the higher the fired bulk density, which increased with firing temperature.

Fired volume shrinkage increased with firing temperature. However, there was no significant difference between samples fired at the same temperature. The variation in water absorption with processed material level was the inverse of that of the fired bulk density. Water absorption of all samples increased with processed material level. Underflow and raw material had similar absorption rates, while those of U2 and U4 were lower. In all cases, water absorption decreased with increasing firing temperature.

The strength of the samples varied with firing temperature but overall, for the clay used, the most effective ash fraction was U4, which gave the lowest water absorption and highest tensile strength, with a 20% clay replacement and firing at 1100°C. However, it should be noted that other clays may give different results and other ash fractions better performance.

Table 7. Test results of fly ash as a clay replacement in fired bricks.

Mix	Fly Ash Content, % by mass	Firing Temperature, °C											
		1000				1050				1100			
		D_f,* g/cm^3	S_v,* %	W_a,* %	F_t,* N/mm^2	D_f, g/cm^3	S_v, %	W_a, %	F_t, N/mm^2	D_f, g/cm^3	S_v, %	W_a, %	F_t, N/mm^2
100% Clay	0	1.9	3.0	13.0	7.5	2.0	5.6	10.5	11.4	2.2	14.1	6.7	18.1
Clay + Raw	10	1.9	3.2	14.2	7.0	2.0	8.0	12.0	11.3	2.1	14.8	7.5	19.6
	20	1.8	3.8	16.3	5.6	1.9	7.7	14.2	8.6	2.0	14.2	10.0	13.7
	30	1.7	3.9	19.5	3.6	1.7	8.6	17.9	6.0	1.9	15.1	12.6	11.4
Clay + Underflow	10	1.9	3.3	14.7	6.7	1.9	7.3	12.4	10.3	2.1	14.9	7.9	16.6
	20	1.8	3.6	16.9	5.3	1.9	7.7	15.5	8.7	2.0	14.0	10.2	13.7
	30	1.7	3.7	19.6	3.9	1.8	7.4	17.4	6.7	1.9	13.7	13.3	10.2
Clay + U2	10	1.9	3.5	13.6	6.6	2.0	8.0	11.1	10.0	2.2	15.3	6.3	19.4
	20	1.9	3.0	13.2	6.2	2.0	8.0	11.1	9.8	2.2	14.9	6.4	20.1
	30	1.9	2.8	13.5	5.6	2.0	7.2	12.1	10.2	2.1	13.7	8.0	15.4
Clay + U4	10	1.9	3.5	13.7	7.0	2.0	7.4	11.4	11.1	2.2	14.6	6.7	21.4
	20	1.9	3.3	14.2	6.5	1.9	8.2	12.0	10.8	2.1	14.9	7.4	20.3
	30	1.8	3.5	15.7	5.2	1.9	8.3	13.6	9.9	2.0	14.0	9.5	15.3

* D_f – Fired Bulk Density, g/cm^3
S_v – Fired Volume Shrinkage, % by volume
W_a – Water Absorption, % by mass
F_t – Tensile Strength, N/mm^2

Potential for Recovered Carbon as a Co-Combustion Fuel

In addition to the main materials used in the applications described above, processing also gave those that were carbon-rich, such as the underflow in primary classification and the froth in froth flotation. The reburning of these high LOI materials in utility boilers is a relatively simple method of utilising this concentrated unburnt carbon.

To assess the combustion properties of high-carbon materials, calorific values of Power Station 3, high LOI processed materials were measured. It was found that the calorific values of the froths were high (up to 15,000 kJ/kg), and therefore, could be used as fuel, giving around half the energy of a typical bituminous coal, in terms of calorific contribution. The test results also indicate that the calorific value of the processed materials was proportional to their LOI.

With the high calorific values of high-carbon processed materials, these could also be used as a proportion of the raw feed in cement manufacture. This would give benefits in raw feed material and fuel cost savings.

CONCLUSIONS

The results confirm that fly ash contains many valuable components that that can be effectively (i.e. economically and efficiently) recovered from long-term stockpiles. The specific aim of processing recovered coal combustion by-products was to separate particles into different fineness fractions, relevant to particular applications and to remove or reduce levels of carbon. Based on the findings of an earlier feasibility study, the most appropriate route to meeting the requirements in terms of economics and least impact on the environment was wet processing. The combined processing system used in this project generally met the requirements for various applications covering low, medium and high economic and environmental value.

However, carbon removal remains difficult because it is so widely distributed in fly ash in terms of size. This means there is a balance between yield of the ultrafine fly ash, which is high value for use as a cement component and minimising carbon. There needs to be more work in this area, since carbon removal also results in separation of a significant amount of the most pozzolanically reactive ultrafine particles.

The fly ash phases recovered were characterised in terms of their physical and compositional properties and, based on these, a series of end use applications were scoped to achieve 100% utilisation. The finer fractions were used as cement components in concrete. The concrete made with processed fractions gave improved consistence and satisfactory strength development compared to that of the PC. The strength obtained with ultrafine fractions gave little or no difference compared to raw material. This may be caused by surface hydration during wet long-term storage and/or processing. Coarse and medium fineness materials were considered in foamed concrete as fine aggregate. A 50% replacement of sand was used and the results gave improved consistence and enhanced strength development compared to the PC mix. It is also suggested that coarse processed fly ash fractions could be used in concrete as an ‘active’ sand replacement.

Processed material used as a lime-soil stabilisation significantly reduced swelling of high sulfate content clay. The fly ash size range most effective for partially replacing clay as a component of fired clay bricks was U4. Test with a kaolin clay used lowered water absorption and increased strength with 20% clay replacement and firing at 1100°C. The removed carbon gave a calorific value of around half that of a typical bituminous coal and clearly could be beneficial as a co-fuel, particularly in Portland cement manufacture, where the included alumino-silicates can contribute to clinker formation. Stockpiles can also yield economically significant quantities of cenospheres (ie those alumino-silicate particles with a specific gravity <1).

The property requirements covered in Standards and Guidance Documents for recently produced fly ash in particular end uses, can generally be followed for processed material. The exception to this is in the material’s use as a cement component, where wet long-term storage can lead to a loss in reactivity. However, small changes to the concrete mix proportions can easily overcome this issue.[17]

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