Managing Change in the Supply of Cement Powders for Radioactive Waste Encapsulation – Twenty Years of Operational Experience

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ABSTRACT

Sellafield Limited operates four encapsulation plants for the immobilisation of intermediate level wastes arising from reprocessing operations. The first of these was commissioned in 1990. These plants use a range of cement formulations based on Portland Cement (CEM I, equivalent to ASTM Type I), Ground Granulated Blastfurnace Slag (GGBS) and Fly Ash (FA). Quality of the waste packages produced by these plants is maintained by operating within process and product envelopes developed during an extensive R&D programme. A specification describing the required properties and performance of each cement powder forms part of the quality system. Where possible, this specification has been aligned with the relevant UK and European specification for cements. However, in some cases, it has been necessary to apply different standards to comply with the quality requirements of nuclear plant operation.

During the past 20 years of plant operation, sustainability and economic challenges as well as regulatory changes have affected the supply of each of these materials. This has resulted in additional R&D work to justify revisions to the Sellafield powder standard, but in some cases it has been necessary to change powders suppliers following closures of plants or failures of suppliers to meet specification. The performance of CEM I has not changed significantly, other than to adapt to regulatory changes. The supply of GGBS from individual steel plants has been relatively stable, but plant closures and restructuring within the steel industry has forced the use of alternative supplies or grinding processes. The supply of FA has been less stable, as its properties are heavily dependent on the source of coal and plant operating parameters used by the selected power station. On two occasions, it has been necessary to change the FA supplier so that powder quality can be maintained.

The experience of the past 20 years has demonstrated the importance of working closely with the cement industry to ensure product quality and the need to monitor changing trends so that supply risks can be recognised early and appropriate mitigation action taken.

INTRODUCTION

The manufacture of cement has evolved over almost two centuries since “Portland Cement” was patented in 1824. During this time, the composition and properties of cement have changed significantly in response to improving scientific understanding and technological changes. In contrast, the nuclear industry in the UK has had only two decades of experience of using cement powders for encapsulation of radioactive waste, but even in this short period, it has already had to respond to significant changes in the quality, composition, performance and availability of cement powders. The sustainability and economic challenges facing the cement industry are already resulting in changes and this trend will continue in future decades. Some of these changes will have the potential to impact on the quality and performance of the cements used for radioactive waste encapsulation. Similar economic and sustainability challenges face the operators of coal fired power stations, where Fly Ash (FA) is produced, and the steelmaking industry, which produces Ground Granulated Blastfurnace Slag (GGBS). Both GGBS and FA are key components of many waste encapsulant formulations, so changes in the quality and performance of these materials may also have an impact on the nuclear industry.

SELLAFIELD ENCAPSULATION PLANTS

There are four ILW encapsulation plants currently operating on the Sellafield site for the encapsulation of reprocessing wastes, as well as plans to develop additional plants for certain historic wastes (see Table I).

Table I Sellafield ILW Encapsulation Plants

Plant	**Commissioning Date**	**Waste Stream**	**Process**
Magnox Encapsulation Plant (MEP)	1990	Magnox Cladding	Grout Infilling (GGBS/CEM I)
Waste Encapsulation Plant (WEP)	1994	Fuel cladding Sludges	Grout Infilling, In-drum mixing (GGBS/CEM I)
Waste Packaging and Encapsulation Plant (WPEP)	1994	Ferric-alumino effluent flocs	In-drum mixing (FA/CEM I/hydraulic lime)
Waste Treatment Complex (WTC)	1996	Plutonium Contaminated Materials	Supercompaction, annulus grouting (FA/CEM I)

The Magnox Encapsulation Plant (MEP) was designed to encapsulate Intermediate Level Wastes (ILW) arising from reprocessing of Magnox fuel at Sellafield and uses an in-drum vibrogrouting process. More than 18,000 drums have been produced.

The Waste Encapsulation Plant (WEP) has been designed to encapsulate oxide fuel cladding wastes and sludges arising from the reprocessing of spent oxide fuel at the Thermal Oxide Reprocessing Plant (THORP), Sellafield using two separate encapsulation processes; a grout infilling process for LWR (Light Water Reactor) Hulls and Ends produced from both Boiling Water Reactor (BWR) and Pressurised Water Reactor (PWR) fuels AGR Hulls produced from Advanced Gas-cooled Reactors (AGR) and technological scrap from the THORP shearing cell; and an in-drum mixing process for two types of waste slurry, Centrifuge cake and Barium carbonate.

The Waste Packaging and Encapsulation Plant (WPEP) was designed to encapsulate Intermediate Level Wastes (ILW) arising from effluent treatment at the Enhanced Actinide Removal Plant (EARP). Effluent from both Magnox and THORP reprocessing at Sellafield is treated in the EARP giving a number of ferric floc wastes for encapsulation at the WPEP using an in-drum mixing process. The WPEP has been operating since 1994. During this time more than ten thousand drums of waste have been encapsulated.

Waste Treatment Complex (WTC) has been designed to immobilise plutonium contaminated material (PCM) currently packaged in containers unsuitable for long term storage. The WTC compacts PCM waste into pucks and immobilises the puck in a cementitious grout.

Each of these plants uses one or more cement formulations developed specifically for the wastes it processes.

Each of these cement formulations has been developed through an extensive R&D programme that has led to the specification of process and product quality envelopes, i.e. a range of acceptable parameters within which it has been demonstrated that an acceptable product will be produced.

The encapsulation plants can therefore be operated in accordance with a quality assurance system which is based upon:

a) The specification of all the parameters which determine the characteristics of the encapsulated product or reflect on the plant operability.

b) The specification of the envelope of these parameters which process development work has shown will guarantee a satisfactory product within plant operating constraints.

c) The ability of the process equipment and controls to ensure that the parameters are maintained within the specified envelope.

In practice, to ensure production of a quality product the plants are operated consistently at “set points” that are well within the control range (or envelope) of each parameter.

The application of these principles provides products of known quality to satisfy the interim storage, transport and long term storage criteria and enable plant throughputs to be achieved.

For example, the key process parameters for the Magnox Encapsulation Plant are given in Table II.

Table II Key process parameters –MEP Encapsulation Grout .

Operating Condition	**Control Range**
Matrix Grout	
BFS/OPC ratio	2.33 to 9.00
Water/Solids wt. ratio	0.31 to 0.37
Grout Temperature	≤30°C
Grout Fluidity	≥200mm Colcrete Flow Channel
Curing time	≥ 10 hrs
Capping Grout	
PFA/OPC ratio	2.33 to 4.00
Water/Solids wt. ratio	0.41 to 0.45
Grout Temperature	≤40°C
Grout Fluidity	≥400mm Colflow
Curing time	≥ 12 hrs
Capping grout delivered to drum	>30kg
Magnox Swarf Filling	
Waste loading	75 kg to 310 kg
Drum vibration	≥25Hz for first 70% of infill ≥10Hz for remaining 30%.
Residual water level	< 55mm in base of drum

CEMENTITIOUS POWDERS USED IN ENCAPSULATION PLANTS

The cement formulations used in these plants are based on three main cement powder components, Portland cement (CEM I, also known as OPC), Ground Granulated Blastfurnace Slag (GGBS, also known as BFS) and Fly Ash (FA, also known as Pulverised Fuel Ash, PFA).

The powders are derived from naturally occurring materials. The supplementary cementitious materials, GGBS and FA are waste by-products of steel and coal-fired electricity production. All such materials are prone to variability. In addition, cement production, steelmaking and power generation are vast businesses geared to their own mass production needs. In comparison, the nuclear industry is an extremely small volume user. Small variations between batches of powders may not be significant to the powder producers, because as long as they remain compliant with national/international quality standards, their products can be sold to the construction industry. However, variations can potentially affect process or product quality in encapsulation plants which operate at "set points" so cannot easily respond to powder variability by adjusting formulations. To minimise the impact of such variability, powders are obtained from single source supplies. In all cases, the powders are required to comply with the appropriate national/international standard, but with certain additional quality requirements being specified where this is necessary to guarantee process or product quality.

Portland cement (CEM I, OPC)

Portland cement (CEM I) is manufactured to the British and European Standard BS EN 197-1:2000 [1]. Although European and US standards differ in various respects, the material is essentially the same as ASTM C150 Type I General Purpose Portland Cement. The material is obtained from a single source and as well as compliance with the standard, the additional requirements are summarised in Table III.

Cement hydration is a series of exothermic reactions leading to temperature rise over the first few days of hydration. The reaction rate is affected by the specific surface area (or "fineness") of the powder, but also by the relative proportions of clinker minerals, with tricalcium silicate being the most reactive. To ensure that the reaction rate is controlled and in particular the maximum temperatures reached at the drum centres remain within acceptable limits, the tricalcium silicate content and fineness are specified by Sellafield Ltd and the latter determined by use of an air permeability method developed by Lea and Nurse as described in BS EN 196-6: 1989 [2]. The European standard is aiming at different performance targets, such as the ability to produce a product with the maximum early and standard strengths (2 and 28 days). Consequently, it is not necessary to specify maximum surface area or reactivity.

Table III Differences Between European Standard and Sellafield Specification for Portland Cement (CEM I)

Criteria	BS EN 197-1 CEM I 42,5 N	Sellafield Ltd CEM I
Tricalcium silicate (Alite)	Total of tricalcium silicate and dicalcium silicate is two-thirds by mass	48-60%
Dicalcium silicate (Belite)		12-24%
Tricalcium Aluminate	-	7-11%
Sodium Equivalent Na_2O_{equiv}	No specified limit, but manufacturer to supply declared mean & certified average variability	≤ 1.00%
Chloride	≤ 0.10%	≤ 0.05%
Fineness (Specific Surface Area)	-	385 ± 65 m^2/kg
Loss on Ignition	≤ 5.0%	≤ 1.5%
Minor Additional Constituent	≤5% w/w	Not allowed unless approved by Sellafield Technical Representative
Cr(VI) Reducing Agent	-	Ferrous sulphate ≤0.5% w/w Stannous chloride ≤0.004% w/w
Additives	Additives allowed ≤1.0% w/w of which organic content ≤0.5% w/w	Not allowed unless approved by Sellafield Technical Representative

The European standard allows for up to 5% Minor Additional Constituents (MAC) which can be inorganic natural mineral materials such as shale, limestone or pozzolan, or else Fly Ash, or Blastfurnace slag. They can be inert or latently hydraulic, and can therefore affect the reactivity of the cement. Due to the range of possible additives, and the different ways in which they can affect cement hydration (both in terms of reaction rates and reaction products), the use of MAC is not currently included in Sellafield cements. For instance, the use of GGBS as a MAC would result in a change in GGBS/CEM I ratio in the grout. If MAC were to be introduced, it may therefore be necessary to adjust plant set-points.

Although the European Standard allows for 5% Loss on Ignition (LOI), the Sellafield Ltd. specification is limited to 1.5%. The higher European limit allows for the decarbonation of limestone which may be present as MAC. The tighter Sellafield requirement limits potential deterioration due to moisture uptake and carbonation; both factors can affect the fluidity and bleed properties of fresh grout.

The total chloride content of Sellafield Ltd CEM I is currently restricted to 0.05%, although the European Standard allows for up to 0.1%. In both cases, the limit is required to minimise corrosion. Waste packages produced in Sellafield encapsulation plants are required to maintain their integrity for a target period of several hundred years, and may potentially degrade by corrosion expansion of the metallic components in the waste or by corrosion of the waste container.

Other differences include restrictions on the type of reducing agent that can be added, and on alkali content.

Ground Granulated Blastfurnace Slag

Ground Granulated Blastfurnace Slag (GGBS) is manufactured to the British and European Standards BS EN 15167-1 [3] and BS-EN 197-1. It is a glassy material comprising mainly calcium and silicon oxides with a number of minor components, whose concentration is dependent on the source of the iron ore. It is a latently hydraulic material (reacts with water) and its hydration is catalysed by the alkalinity generated during CEM I hydration. Its reaction rate is slow compared to CEM I, so it acts to reduce the early exotherm temperature, whilst ensuring good long-term strength development, and reducing porosity.

The material used by Sellafield is obtained from a single source and in addition to compliance with the standards, the additional requirements are summarised in Table IV. Although the Sellafield Ltd specification differs in several ways from the European standards, perhaps the most significant are in surface area, and the use of grinding aids.

There is a high demand for GGBS in the cement industry as a replacement material in cement blends. However, the cement industry requires a material with rapid early strength, which is achieved by finely grinding the GGBS. The European standard therefore specifies a minimum specific surface area of $\geq 275\ m^2/kg$, whereas the Sellafield specification gives a range of $260 \pm 50\ m^2/kg$ to ensure an acceptable reaction rate.

Grinding aids are generally used in GGBS production, but are currently excluded from Sellafield Ltd material. Their effect on process and long-term product properties is unknown.

There are also limits to chemical composition, including chloride.

Table IV Differences Between European Standard and Sellafield Specification for GGBS

Criteria	BS EN 15167-1 GGBS	Sellafield Ltd GGBS
Fineness (Specific Surface Area)	$\geq$ 275 m^2/kg	260 ± 50 m^2/kg
Na_2O	No specified limit	$\leq$ 0.6%
K_2O	No specified limit	$\leq$ 1.0%
Fe_2O_3	No specified limit	$\leq$ 1.0%
Al_2O_3	No specified limit	$\leq$ 15%
Chloride	$\leq$ 0.10%	$\leq$ 0.05%
Density	No specified limit	2.85-3.00 g/cm^3
Grinding Aids	Grinding aids allowed ≤1.0% w/w of which organic content ≤0.2% w/w	Not allowed unless approved by Sellafield Technical Representative

Fly Ash

Fly ash is a siliceous material consisting mainly of reactive SiO_2 and Al_2O_3. It is “pozzolanic”, so reacts with the calcium hydroxide released during cement hydration to give a cementitious product. Like with GGBS, the rate of reaction is relatively low compared to CEM I, so it assists in maintaining low exotherm temperatures. Due to the spherical morphology of the FA particles, it is used in formulations that require high fluidity, such as the capping grouts used to reduce loose contamination and minimise voidage at the top of wasteforms.

Fly Ash is manufactured to the British and European Standards BS EN 450 [4] and BS EN 197-1. The material used by Sellafield is a Type S material (this categorisation is based on limits to the amount of material exceeding 45µm using a wet sieving technique). In addition to compliance with the standard, the additional requirements are summarised in Table V.

Table V Differences Between European Standard and Sellafield Specification for Fly Ash

Criteria	BS EN 450-1 FA Type S, Category B	Sellafield Ltd PFA
Sodium Equivalent Na_2O_{equiv}	≤5.0% (acid soluble)	≤0.30% (water soluble). Acid soluble data (≤5.0%) to be accepted provided acid soluble Na_2O_{equiv} does not vary by greater than ±0.5%.
Loss on Ignition	2-7%	≤7.0%
Moisture Content	No specified limit	$\leq$ 0.5%
Chloride	$\leq$ 0.10%	$\leq$ 0.05%
Density	±0.2 g/cm^3 from a declared value	≥2.0 g/cm^3

The Sellafield specification is not substantially different from the European Standards although like the other materials, it is obtained from a single source to minimise variability.

Differences include chloride content (0.05% for Sellafield specification) and moisture content (0.5%)

Performance Criteria

In addition to the powder specifications, the powders are required to comply with performance criteria which are checked by the suppliers on a batch basis. Key criteria are also measured on plant during production and periodically during storage at the plants to ensure the powders remain within specification. These performance criteria are measured on small scale batches of standard grouts (by the supplier) or on samples taken from the mixers (by the plants). These criteria include grout density, fluidity, setting time and bleed. Fluidity is a key criterion, as the grouts are required to fully penetrate the waste including for instance, the small gaps between the fins of Magnox elements. Fluidity is measured by the Colcrete Flow Channel ("Colflow") technique, a proprietary fluidity test developed by Colcrete Ltd, [5] in which a standard volume of grout is allowed to flow along a horizontal channel. The fluidity must be maintained for a set period after mixing (up to 2.5 hours).

POWDER SUPPLY HISTORY

The Sellafield Ltd powder specification was first developed by BNFL during an R&D program between 1983 and 1989, when it was first used as a purchasing specification for Magnox Encapsulation Plant. Since then, there have been several changes in powder supply, which have necessitated revisions of the specification. The most significant changes have been in response to supply issues with powder performance implications. However, changes in the British and European Standards have also resulted in changes to the Sellafield specification. The necessary response to such changes is to carry out sufficient experimental work to assess what effect the change will have on process or product performance, prior to introduction of the new powder to the encapsulation plants.

It is important to recognise that the nuclear industry has limited ability to control the supply of these powders, other than to specify which plant/supplier will be used, and to negotiate a buffer storage capacity of powders which have passed Sellafield acceptance testing. As a very minor user, consuming of the order of 1000te per year of each powder in a Mte market, there is significant pressure to use standard materials rather than arrange small batches of special grinds and occupy valuable silo space with materials that turn over at a low volume rate.

OPC Supply History

The history of OPC supply has been the least problematic of the three powders. Having been supplied from the same plant since 1989, the changes have only been in response to regulatory change, including the transition from British to European standards. Nevertheless, assessments of potential alternative supplies have been carried out periodically. For instance, EU Directive 2003/53/EC required the introduction of reductants to limit Cr^{VI} in cement powder. In preparation for this change, a range of alternatives supplies was assessed. This involved the investigation of two reductants, tin (II) chloride and iron (II) sulphate, and the establishing of maximum reductant contents.

During the period of supply, the tendency in the cement industry has been towards increased fineness, allowing cements to develop the required early strength despite the addition of increased amounts of supplementary cementitious materials and MAC. Sellafield has been able to adapt to this trend, which has been off-set by a change of GGBS supply (see below) to one of lower surface area and therefore lower reactivity. To balance this, and maintain overall reactivity, fluidity, etc unchanged, the fineness of the Sellafield specification CEM I was increased.

GGBS Supply History

The supply of GGBS since commissioning of MEP in 1990 has been against a background of change in the steel industry. Initially, GGBS supplies were obtained from a steelworks in Scotland (Ravenscraig). However, closure of this plant in 1992 required a managed transfer to an alternative supplier in England (Redcar). In preparation for this transfer, a buffer supply of 5000te of dried, unground Ravenscraig slag was placed in storage. A successful transfer to Redcar GGBS took place in 1993, after which the remaining Ravenscraig slag was held as a contingency. However, this supply became contaminated due to poor segregation from other materials held in the same facility, and it had to be disposed of. Prior to the decision to transfer to Redcar, an assessment was made of supplies from 11 alternative sources. For instance, Figure 1 shows that average fineness results did not change following the transfer. However in 2003, due to restructuring of the supply arrangements, grinding of the GGBS was carried out by a different company. To maintain a supply that met the Sellafield specification, a blend of finely ground product with coarse "grits" was developed (see Fig 1). The bimodal particle size distribution gave an improved performance at a lower overall fineness. As a result, the fineness specification for Sellafield GGBS is now less than the minimum in the European standard.

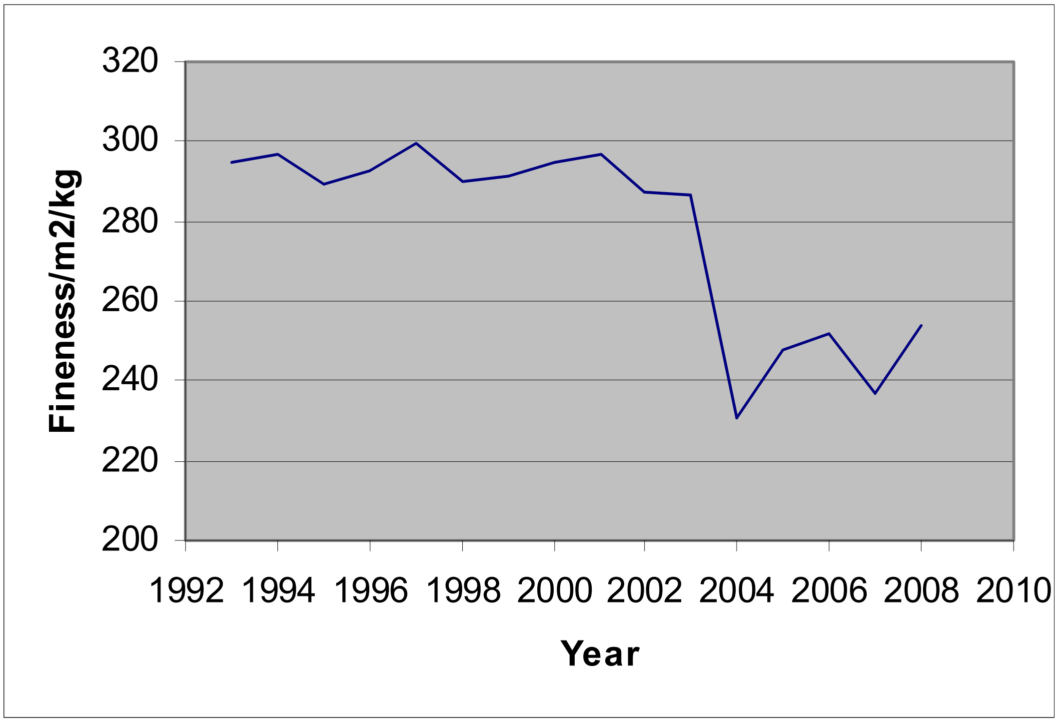


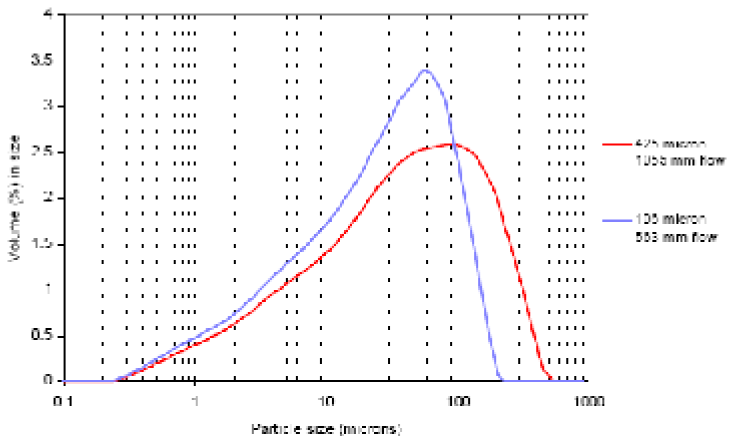
Fig. 1 Mean Annual Fineness of BFS supplied to Sellafield 1992-2008

A reliable supply continued from Redcar until spring 2009, when a decision was taken to close the plant. An alternative supply has been identified and a managed process to transfer to the new supply is on-going.

Although specific surface area is the criterion used in the Sellafield specification, it is important to recognise that the performance of GGBS relies on more complex features of particle size distribution. Understanding such underlying factors has been an important principle in the strategy for powder management.

To that end, a major program of research was carried out in conjunction with Nottingham University to improve the knowledge of the effect of particle size distribution on key performance criteria of the various cement powders including GGBS. Although the results of this work are too extensive to report here, examples are given below that illustrate how particle size distribution in GGBS affects fluidity and bleed for 9:1 GGBS/CEM I blends. Figure 2 shows how the initial fluidity (millimetres Colflow against a 400mm minimum target) of grouts has been affected by modifying the particle size distribution. The modification was achieved by "scalping" to remove all particles exceeding a selected size, in this case 425 µm and 106 µm. From Figure 2 it can be seen that the primary difference between the two distributions is the increased proportion of coarse material as a result of the coarser scalp. This results in an overall broadening of the distribution and a considerably higher fluidity for the coarser scalp.

Fig. 2. Effect of increased scalping size on GGBS distributions and effect on grout fluidity



Although high grout fluidity is an important requirement, the volume of bleed produced by grouts should also be limited as much as possible. In Figure 3 the particle size distributions and bleed volumes are shown for grinds from a range of different GGBS sources, all of which have been ground to a nominally similar 98% passing size (the 98th percentile size on the cumulative percentage undersize plot of the particle size distribution). Bleed is the volume of water on a 100ml sample immediately after mixing. The results are for high water/solid ratio blends (w/s = 0.4 for all blends except the reference blend, which was 0.37). The bleed for the reference blend can be assumed to be in excess of this figure. It is difficult to isolate the effect of PSD on bleed volume due to the differences in the overall distribution from each raw material, and the resulting fluidity difference. However, it is seen that lower bleed volumes were associated with the powders containing a higher proportion of sub 20 µm material.

In broad terms, this research program showed that for GGBS the coarse end of the particle size distribution controls fluidity whilst the finer end influences bleed volume.   A balance between these two elements is required for all round high grout performance.

This fundamental understanding of the criteria affecting powder performance allows informed decisions to be taken when selecting GGBS supplies.

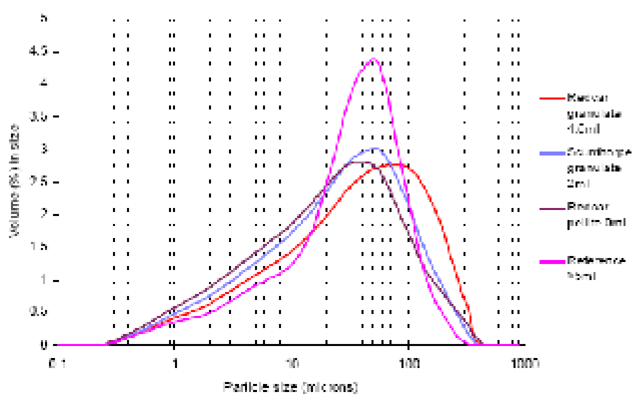


Fig. 3. Nominally similar d_{98} grinds for a range of GGBS Sources and associated bleed volume at 9:1 GGBS/CEM I

FA Supply History

The supply of FA has provided the greatest challenge and requires significant on-going attention. As a waste product, it is highly dependant on the quality of the materials burned in coal fired power stations, and is also subject to changes resulting from the power station operators' responses to changing environmental regulations. The changes in FA supply are summarised below, but this hides substantial on-going work on a regular basis throughout this period to assess alternative supplies due to issues such as poor fluidity.

The variability of FA supply has resulted in a number of changes in supplier over the years. Supplies commenced in 1989 from Fiddlers Ferry power station. However, by 1993, the performance as measured by Colflow fluidity tests[1] (see Figure 4) had deteriorated to the extent that an alternative source was required. The deterioration in quality coincided with a change to use of imported coal, and increased loss on ignition. Supplies were then obtained from Ferrybridge power station until 1999, when similar quality problems (low fluidity, high LOI) forced another supply change, this time to Drax power station. Supplies from this source have been satisfactory over a period of 10 years, although there has been a gradual downward drift in fluidity and an increase in LOI. The increasing LOI is a result of tighter emissions standards forcing the power stations to operate at lower temperatures to reduce NOx emissions, but with the additional effect that the percentage of unburnt carbon in the ash is increased.

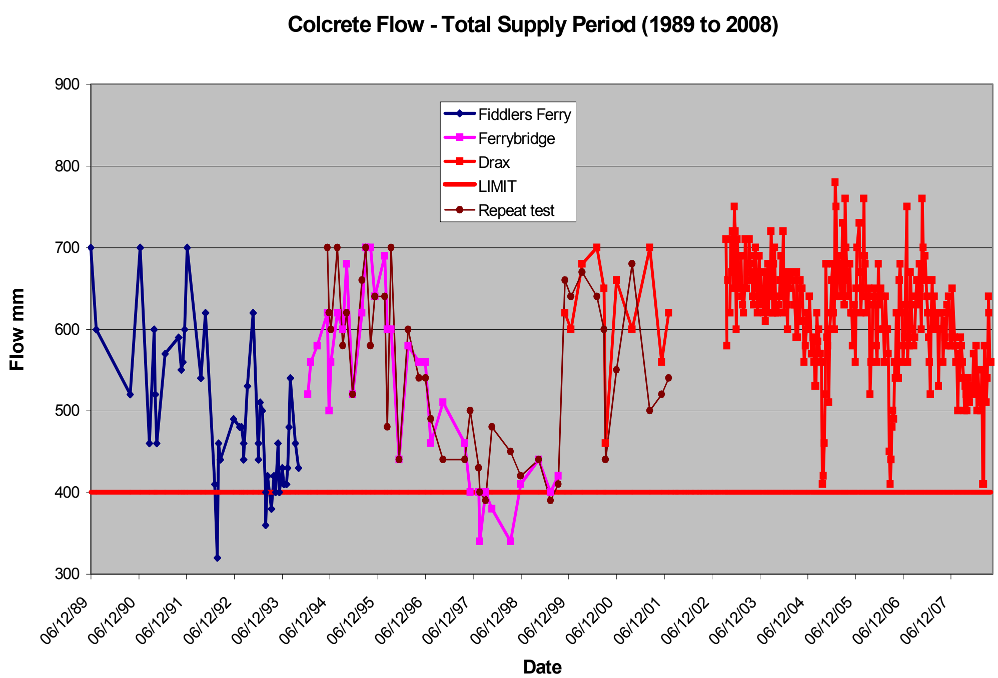


Fig. 4. Variability in Fluidity of PFA over Total Supply Period as Measured by Suppliers (currently Cemex)

MANAGING RISK TO POWDER SUPPLIES

The experience of the past 20 years has shown us that changes in the performance of cement powders are inevitable, and that the nuclear industry has little influence on these changes. Although we will continue to monitor the quality of cement powders and analyse trends, this is not enough to ensure continuing supply of suitable materials. It is also important to maintain awareness of the external influences on the cement, steel and coal-fired generation industries and to maintain good working relationships with the key powder suppliers so that the maximum advance notice of change can be anticipated.

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[1] Analyses as provided by powder suppliers, currently Cemex UK Ltd

Potential Changes in Portland Cement (CEM I) Performance and Supply

The most significant driver for the cements industry over the past few years has been sustainability, and more particularly CO_2 emissions, and there is little doubt this will remain a major driver in years to come. Cement clinker manufacture currently accounts for 5% of global CO_2 emissions. Total production increased by 55% through the 1990s and was set to reach 2.8 times 1990 levels by 2020 before the current recession. An average of 0.87 te CO_2 is emitted during production of each tonne of cement clinker (2004 figures), 60% from calcination of limestone, 30% from fuel to heat the kiln, and the rest from grinding, transport etc. [6].

The main response to sustainability issues has been, and will continue to be increased use of supplementary cementitious materials such as GGBS and FA. The mineral composition of cement clinker itself is unlikely to change significantly. However, minor changes that might be anticipated include higher chloride content, due to increased use of alternative fuels including chlorinated waste, increased fineness to balance the lower reactivity of the supplementary cementitious materials. Changes in other minor components may occur, such as increased phosphorus content due to burning of animal meal. This may have a minor effect on hydration rates and hydration products, particularly of the dicalcium silicate phase [7], but is unlikely to have a significant effect on performance.

Of these trends, the most significant issue for the nuclear industry will be the increased chloride content. The BS EN standard is for a maximum of 0.1% chloride, but the Sellafield specification allows only 0.05%. The cement industry will of course, aim to work within the European standard and cannot readily respond to the needs of small users such as the nuclear industry.

Potential Changes in Fly Ash Performance and Supply

The loss on ignition (LOI) of FA has been moving steadily upwards in recent years, and is regularly close to the maximum. This is due to an increase in unburnt carbon, resulting from power station operators running at lower furnace temperatures to stay within new NOx emission limits. Variability in FA supply is therefore a current reality.

However, due to the high volumes produced, it is important to the operators that the ash can still be used as a product rather than disposed as a waste, and as the European standard (for Category B ash) and the Sellafield standard have the same maximum LOI (7%), there is mutual interest in resolving the problem. Therefore, there is increasing investment in processes for beneficiation of the ash by various processes to remove unwanted material and improve its reliability as a cementitious product. One solution is recovery and beneficiation of lagoon stored historic material. For instance, a plant at Fiddlers Ferry, expected to be commissioned in 2009 will use 4 stages to process historic Fly ash – to split into cenospheres, carbon, magnetite and ash (both class A and S).

Fluidity has also been a challenge for some years. The beneficiation processes which will reduce LOI will also produce materials with improved fluidity.

Therefore, despite historic supply difficulties, the supply consistency is likely to improve in the future.

Potential Changes in Ground Granulated Blastfurnace Slag Performance and Supply

The chemical composition of BFS from any single steel plant remains largely stable. The most significant variability comes from the method of cooling, which will affect the crystallinity and therefore reactivity, and from the grinding process which affects particle size distribution, and therefore will also affect reactivity. These can to a large extent be controlled, so that it is expected that a suitable supply of BFS will be available from a range of potential suppliers.

However, the economic cycle is likely to affect the viability of individual steelworks, and it is therefore important to maintain awareness of the availability and performance of alternative sources. In the longer term, beneficiation of iron ore at point of extraction, increased use of recycled steel and technological developments in iron production may affect the quality and availability of GGBS in the future. Although this is unlikely to have significant implications to current operating encapsulation plants, it is an area that will require monitoring over the next few years.

CONCLUSIONS

Intermediate level waste encapsulation plants have operated successfully at Sellafield and elsewhere in the UK nuclear industry over the past twenty years, using a range of cement formulations based on Portland Cement, Fly Ash and Ground Granulated Blastfurnace Slag. During this time, there have been significant changes in the national and international standards covering these materials, as well as changes in the manufacture and availability of the powders. The risk that these changes might affect the performance of the cement formulations and therefore the quality of the waste products has been effectively managed by the application of a quality management system built around a specific nuclear industry standard, and by commercial arrangements that use single source supplies to ensure compliance with these standards through reduced powder variability.

The monitoring of trends in the key performance criteria for each of these powders has given advance warning of potential supply issues. For instance, on two occasions over the past 20 years, trends in fluidity of Fly Ash formulations have required a change in supply.

Prior assessment of a range of alternative supplies has allowed managed change where this has become necessary due for instance to plant closures. In the case of GGBS, 11 alternative sources were investigated once the risk of closure of the Ravenscraig steelworks was recognised.

Comparison of the performance of “Sellafield standard” with European standard powders has allowed the managed introduction of change and the harmonisation of the two sets of standards where appropriate. For instance this was essential with the introduction of a regulatory requirement to dose CEM I with reductants to reduce Cr^{VI}. However, this has not always been appropriate, and in some cases, it has been necessary to retain different criteria in the Sellafield standard. For instance, the fineness of Sellafield GGBS is significantly lower than the European standard.

The nuclear industry is a minor user of these powders and in many respects must be prepared to adapt to the changes imposed (e.g. sustainability issues). Therefore it is necessary to;

- carry out R&D work to justify the aligning of Sellafield requirements with European standards wherever possible;
- monitor current performance of all powders and anticipate future trends in their production and;
- maintain awareness of the availability and performance of alternative supplies.

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