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Analisi di best practice per la predisposizione di linee guida finalizzate a promuovere l'utilizzo delle ceneri di carbone in campo geotecnico

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Riassunto

Il presente documento costituisce il Rapporto di Avanzamento previsto nell'ambito del Contratto di Ricerca di Sistema 2001 relativo al Progetto **COMPA**, Sottoprogetto **PERFORMA**, Attività **"Linee guida per procedure di caratterizzazione dei rifiuti al fine del loro riutilizzo"** sub-attività *"Predisposizione delle Linee guida*".

Obiettivo dell'incarico è la predisposizione di linee guida "tematiche" per la qualificazione ambientale di rifiuti di particolare interesse del Settore Elettrico in relazione a specifiche forme di potenziale valorizzazione e riutilizzo degli stessi attualmente non contemplate dalla relativa legislazione (D.M. 5/2/98) al fine di una sua successiva possibile integrazione.

Ciascuna linea guida, a partire dalla progettazione dello studio di recupero del rifiuto, dovrà individuare, mettere a punto ed applicare sperimentalmente procedure di analisi atte ad attestarne la compatibilità ambientale, verificando le assunzioni fatte a livello teorico. Particolare riferimento verrà fatto alle procedure di caratterizzazione di base dei rifiuti il cui sviluppo è in parte già in atto in ambito CEN (TC 292 "Characterisation of waste").

Quale obiettivo specifico dello studio, il presente Rapporto si propone di valutare la possibilità di utilizzare, in condizioni tecnicamente ed ambientalmente sicure, **le ceneri di carbone per la realizzazione di rilevati e sottofondi stradali**.

Il Rapporto intende fornire una analisi di *best practice* relativa a tali forme di reimpiego e, in particolare,:

- presenta una sintesi delle caratteristiche chimico-fisiche delle ceneri di carbone e dei loro principali settori di riutilizzo;
- evidenzia i principali dati nazionali ed internazionali di produzione e destinazione;
- valuta l'attuale quadro legislativo e normativo, nazionale ed internazionale;
- richiama i principali vantaggi tecnici legati alle forme di riutilizzo più consolidate;
- analizza in maggior dettaglio gli aspetti tecnici relativi all'impiego delle ceneri di carbone per la realizzazione di:
  a) rilevati strutturali,
  b) sottofondi stradali,
  c) riempimenti,

  al fine di confermare la validità tecnica di tali applicazioni e di valutarne le modalità e le condizioni di interazione con l'ambiente circostante;
- sintetizza preliminarmente i risultati e le considerazioni sulla compatibilità ambientale delle ceneri per impieghi geotecnici così come emergono dall'indagine di best practice;
- riassume il quadro normativo in corso di definizione a livello Europeo per la caratterizzazione ambientale dei rifiuti, con particolare riferimento all'attività portata avanti nell'ambito del comitato tecnico CEN TC 292 "Characterisation of wastes".

INDICE

Elenco delle Tabelle .... **Pag. 5**

Elenco delle Figure .... **Pag. 6**

1. Approccio generale .... Pag. 7

2. Le ceneri di carbone

2.1 Caratteristiche generali .... Pag. 9

2.2. Potenzialità di riutilizzo .... Pag. 14

2.3. Quadro legislativo .... Pag. 16

2.4. Quadro tecnico normativo

2.4.1. Situazione in Europa .... Pag. 18

2.4.2. Situazione negli USA .... Pag. 22

2.5. Dati di produzione e destinazione

2.5.1. Situazione in Europa .... Pag. 24

2.5.2. Situazione negli USA .... Pag. 28

2.6. Prodotti e tecnologie di riutilizzo

2.6.1 Cementi e calcestruzzi .... Pag. 30

2.6.2 Laterizi .... Pag. 30

2.6.3 Aggregati artificiali leggeri .... Pag. 31

3 Le ceneri nella realizzazione di rilevati e sottofondi stradali

3.1 Aspetti tecnici

3.1.1 Rilevati e riempimenti strutturali .... Pag. 32

3.1.2 Miscele fluide .... Pag. 35

3.1.3 Sottofondi stabilizzati .... Pag. 38

3.1.4 Evoluzione normativa in corso .... Pag. 42

3.2 Aspetti ambientali

3.2.1 Considerazioni generali sui potenziali impatti ambientali legati all'impiego di materiali non convenzionali in applicazioni geotecniche .... Pag. 45

3.2.2 La caratterizzazione ambientale dei rifiuti e l'attività normativa in corso .... Pag. 46

3.2.3 Valutazioni preliminari sul comportamento ambientale delle ceneri di carbone .... Pag. 49

Conclusioni .... Pag. 59

ALLEGATI:

Allegato 1 Standard ASTM PS 23-95 "Guide for the Use of Coal Combustion Fly Ash in Structural Fills" **……………………………..** **Pag. 60**

Allegato 2 "Fly Ash Facts for Highway Engineers" (Rep. FHWA-SA-94-081) U.S. Dept. of Transportation, Fed. Highway Adm., USA 1995 **……** **Pag. 70**

Allegato 3 UKQAA Technical Datasheets: **……………………………………** **Pag. 113**
2 - Fill: How PFA/fly ash can be used for fill application
6.0 - FABM's: Fly Ash Bond Mixtures for road and airfield pavements
6.1 - GFA's: Lime and cement bound granular fly ash mixtures for use as a sub-base and road base layer
6-4 - Fly ash in CBM: How fly ash can be incorporated in cement bound mixtures
6.5 - LFA : Lime Fly Ash for Capping and Sub-Base
Environment: PFA/fly ash and environmental considerations

Allegato 4 Proposta di norma tecnica comunitaria pr EN (TC 227 WI 190) "Unbound and hydraulically bound mixtures - Part 3: Fly ash bound mixtures - Definitions, composition, classification" **…………** **Pag. 136**

Allegato 5 Proposta di norma *pr EN (TC 227 WI 191)* "Unbound and hydraulically bound mixtures - Part 4: Fly ash for hydraulically bound mixtures - Definitions, composition, classification" **………...** **Pag. 157**

ELENCO DELLE TABELLE

Tabella 1 - Contenuto percentuale dei principali componenti delle ceneri e confronto con le pozzolane naturali

Tabella 2 - Confronto tra le concentrazioni elementari nel carbone, nel suolo e nella crosta terrestre [*Reported data IEA 1992*]

Tabella 3 – Composizione elementare media nel carbone e nelle ceneri (Tabella tratta da "Status Report on Healt Issues Associated with Pulvertised Fuel Ash and Fly Dust" KEMA (NL) 1998)

Tabella 4 - Coal Combustion By-Products: Applications and Competing Materials (Tabella tratto da Western Region Ash Group, http:/www.wrashg.org/westuse.htm)

Tabella 5 - Tipi di cemento e loro composizione - Percentuali in massa (UNI ENV 197/1)

Tabella 6 - Requisiti di controllo qualità delle ceneri secondo la UNI EN 450

Tabella 7 - Produzione ed Utilizzo di Residui termoelettrici nel 1999 in Europa (in migliaia di tonnellate)*

Tabella 8 - Produzione di rifiuti termoelettrici in USA (anno 1999, fonte ACAA –American Coal Ash Association)

Tabella 9 - Requisiti di controllo qualità per le ceneri siliciche previsti in base alla pre-norma prEN (TC 227 WI 191)

Tabella 10 - Annex C alla proposta di norma Europea prEN (TC 227 WI 190): Examples of fly ash bound mixtures (FABM) for road and airfield construction using siliceous fly ash

Tabella 11 - Proprietà chimico-fisiche di un generico rifiuto rilevanti dal punto di vista ambientale

Tabella 12 - Metodi di caratterizzazione contemplati negli standard sviluppati dal CEN / TC 292 "Characterization of waste" rilevanti per la qualificazione ambientale delle ceneri di carbone negli impieghi geotecnici

Tabella 13 - Intervalli di concentrazione dei macro-elementi nelle ceneri (da "The development of an environmental code of practice for use of pfa as a fill material" UKQAA)

Tabella 14 - Intervalli di concentrazione degli elementi in tracce nelle ceneri (da "The development of an environmental code of practice for use of pfa as a fill material" UKQAA)

Tabella 15 - Analisi lisciviati da test di cessione sulle ceneri leggere (da "The development of an environmental code of practice for use of pfa as a fill material" UKQAA)

Tabella 16 - Intervalli di composizione nel prodotto di lisciviazione da stoccaggi reali di ceneri in mucchio (da "The development of an environmental code of practice for use of pfa as a fill material" UKQAA)

ELENCO DELLE FIGURE

Figura 1 – Ceneri leggere di carbone osservate al SEM

Figura 2 – Distribuzione granulometrica di un campione tipico di ceneri leggere di carbone

Figura 3 - Production of CCPs in Europe in 1999 (dati estratti da *www.ecoba.com)*

Figura 4 - Utilization of fly ash in the construction industry and underground mining in Europe in 1999 (dati estratti da *www.ecoba.com*)

Figura 5 - Principali settori di impiego delle ceneri di carbone negli USA

Figura 6 - Concentrazioni medie di elementi in tracce nelle ceneri di carbone

Figura 7 - Concentrazioni medie di elementi in tracce nei prodotti di lisciviazione ottenuti da ceneri di carbone applicando differenti metodologie di prova

1. Approccio generale

Ogni ipotesi di incorporare un materiale non convenzionale, ed in particolare un rifiuto o un sottoprodotto, all'interno di un prodotto industriale e parimenti, in questo caso, in una applicazione geotecnica, richiede, oltre alla valutazione di questioni di tipo tecnico-ingegneristico, economico e di operatività pratica, l'esame di aspetti di tipo ambientale, di sicurezza del lavoro e di riciclabilità a fine vita dei prodotti risultanti.

In un percorso tipico di valutazione dell'utilizzabilità di un nuovo materiale possono essere individuati i seguenti passi:

- identificare gli aspetti tecnici, ambientali, di sicurezza, di riciclabilità ed economici associati al materiale in riferimento alla applicazione considerata;
- individuare prove di laboratorio, procedure e criteri di valutazione standardizzati cui il materiale deve rispondere al fine della sua accettabilità in relazione ai precedenti aspetti rilevanti per l'applicazione considerata;
- eseguire le precedenti prove e verifiche;
- considerare la possibilità, se il materiale non soddisfa il precedente punto, di modificare il materiale o il prodotto prima di rigettare l'ipotesi di utilizzo;
- identificare gli aspetti che possono rappresentare dei vincoli importanti all'implementazione pratica della ipotesi in esame (ad es. accettabilità istituzionale, politica, pubblica);
- determinare la necessità di una eventuale applicazione dimostrativa o di valutazioni supplementari per supportare ulteriormente l'ipotesi di utilizzo considerata in risposta alle riserve evidenziate al punto precedente.

Durante l'iniziale fase di individuazione degli aspetti rilevanti, particolare attenzione deve essere rivolta alla raccolta della documentazione già disponibile, costituita da precedenti prove di laboratorio, casi applicativi e analoghi progetti già condotti in passato, al fine di evitare inutile ripetizione di precedenti sforzi.

La fase di valutazione iniziale andrà evidentemente condotta in maniera specifica caso per caso; tuttavia, allo scopo di meglio chiarire il percorso di analisi, è possibile indicare a titolo esemplificativo i seguenti punti di indagine.

Fra gli aspetti tecnici:

- quale è il ruolo del materiale considerato nella applicazione in esame;
- quali sono le caratteristiche fisico-chimiche del materiale proposto rilevanti per la qualità del prodotto finale;
- quali sono i metodi ed i criteri messi a punto per i materiali convenzionali che possono essere adottati per misurare e valutare le precedenti caratteristiche rilevanti.

  A riguardo di questi ultimi si tratta in gran parte, nel settore delle applicazioni geotecniche, di correlazioni empiriche in cui l'esperienza applicativa di decenni ha legato le caratteristiche misurate nelle prove sui materiali convenzionali con le prestazioni in campo delle opere finite. E' spesso necessario, pertanto, verificare l'estendibilità di prove e criteri convenzionali ai nuovi materiali in esame e valutare l'esigenza di eventuali modifiche e sperimentazioni.

Fra gli aspetti ambientali, è necessario prendere in considerazione, ad esempio,:

- quale è la classificazione del materiale in base alle vigenti legislazioni sui rifiuti;

- quali sono i componenti chimici o le caratteristiche fisiche del materiale potenzialmente pericolose per l'ambiente;
- quali sono le operazioni cui il materiale può essere sottoposto durante le fasi di utilizzo (pretrattamento, stoccaggio, movimentazione, produzione/costruzione, manutenzione, gestione a fine vita) di potenziale impatto per l'ambiente.

  E' necessario a tal punto definire opportuni criteri per stabilire i tenori massimi accettabili per i costituenti inquinanti sia in riferimento alla composizione del materiale che ai suoi potenziali rilasci (emissioni e lisciviati).

In relazione agli aspetti di sicurezza dell'ambiente di lavoro, nell'analisi di compatibilità andranno considerati aspetti quali:

- le proprietà (fisiche o chimiche) del materiale o del prodotto che possono risultare rilevanti;
- le modalità di erronea esposizione al materiale da parte dei lavoratori durante le fasi di utilizzo dello stesso.

  Andranno in tal caso determinati i test di campo e di laboratorio più opportuni per caratterizzare i potenziali rilasci di polveri, fumi o liquidi pericolosi dal materiale considerato in relazione alla specifica applicazione proposta e stabilire i criteri di protezione da adottare.

Non andranno, inoltre, trascurati gli aspetti di valutazione legati alla gestione a fine vita del prodotto in cui si ipotizza di utilizzare il materiale in esame; fra questi:

- quale la potenziale riciclabilità del prodotto a fine vita;
- quali le proprietà fisico-chimiche del materiale che possono influenzare negativamente tali potenzialità, sia dal punto di vista tecnico che ambientale o di sicurezza;

Infine, tra gli aspetti di tipo economico da prendere in considerazione vi sono, ad esempio, i seguenti:

- quali sono i costi di messa a discarica evitati a seguito del riutilizzo del materiale;
- quali sono gli eventuali costi (o risparmi) addizionali di progetto, costruzione o manutenzione legati all'adozione del materiale non convenzionale considerato;
- in che misura la vita utile e la gestione a fine vita del prodotto vengono influenzate dall'introduzione del materiale in esame.

Nonostante l'apparente complessità del precedente percorso valutativo, nel caso di molti rifiuti e sottoprodotti, e fra questi certamente le ceneri di carbone, evidenti vantaggi tecnici ed economici hanno già, di fatto, anticipato a molti anni or sono la loro adozione pratica, precedendo la stesura delle norme di controllo ed utilizzo e verificando direttamente in campo i principali aspetti di compatibilità con l'ambiente naturale e di lavoro. Le loro proprietà e modalità di utilizzo hanno trovato successiva conferma nelle relative norme tecniche di settore e molti studi ne hanno confermato gli aspetti di accettabilità ambientale. Tuttavia, specie in quest'ultimo settore, ulteriori approfondimenti e conferme sono necessarie in conseguenza della accresciuta capacità di analisi e di valutazione degli effetti dell'attività antropica sull'ambiente e della sempre maggior pressione da essa esercitata sulle capacità di attenuazione di quest'ultimo, che impone un livello di attenzione sempre più alto.

Nei successivi capitoli verrà presentata una sintesi di quanto emerge dalle esperienze consolidate internazionalmente in relazione all'impiego in campo geotecnico delle ceneri di carbone, evidenziando inoltre le ulteriori esigenze di approfondimento necessarie per il completamento dell'attività prefissatasi dal progetto.

2. Le ceneri di carbone

2.1 Caratteristiche generali

Le ceneri leggere rappresentano il particolato solido trattenuto dagli elettrofiltri adottati per il trattamento dei fumi di combustione nelle centrali termoelettriche alimentate a carbone.

Il carbone è, come noto, il prodotto della trasformazione di sostanze vegetali che sono gradualmente passate, in determinate condizioni climatiche e geologiche, dallo stato di accumuli organici agli stati successivi di torbe, ligniti, litantraci ed antraciti.

Durante il processo di deposizione e subsidenza dei resti vegetali nell'originaria torbiera da cui ha avuto inizio la complessa serie di trasformazioni chimico-fisiche di carbonificazione, una piccola frazione di sostanze minerali (principalmente quarzo, feldspati, argille, pirite, calcite, carbonati, solfati) si è depositata inevitabilmente insieme al materiale organico, formando la frazione inerte del successivo carbone.

Le ceneri sono il risultato del processo di trasformazione subito dalle impurità minerali (la precedente frazione minerale) presenti nel polverino di carbone durante la sua combustione in caldaia.

Esse, di natura silico-alluminosa, fondono durante il processo di combustione ad alta temperatura (1400-1500 °C). La maggior parte di esse, le ceneri leggere, viene trascinata dai fumi e, man mano che questi si raffreddano in uscita dalla caldaia, ricondensa sotto forma di piccole particelle sferoidali su cui si depositano inoltre parte degli elementi a più basso punto di ebollizione precedentemente passati in fase vapore. Le particelle solidificate di ceneri leggere vengono successivamente captate dagli elettrofiltri e, dopo essere estratte dalle sottostanti tramogge di accumulo per via pneumatica, raccolte negli appositi sili di stoccaggio in forma secca.

Il contenuto medio di ceneri nei carboni fossili utilizzati in Italia è stimabile intorno al 13% in peso. Una frazione minore di esse (10-15 %) cade direttamente sul fondo della caldaia da cui viene raccolta con sistemi di estrazione generalmente a secco ed è denominata "cenere pesante", distinguendosi appunto dalla frazione principale (85-90%) costituita dalle precedenti "ceneri leggere" o "volanti".

Le caratteristiche chimiche e fisiche e, conseguentemente le proprietà tecnologiche ed il comportamento ambientale, delle ceneri leggere dipendono da numerosi fattori quali il tipo di carbone, la miniera da cui è stato estratto, le condizioni di preparazione e combustione (macinazione, temperatura, tipologia di caldaia).

In Figura 1 è riportata la fotografia al microscopio elettronico a scansione di una particella tipica di cenere leggera. La dimensione di queste è generalmente compresa tra 1 e 100 μm e prevalentemente (per il 70-80%) inferiore a 40 μm, paragonabile a quella di un cemento.

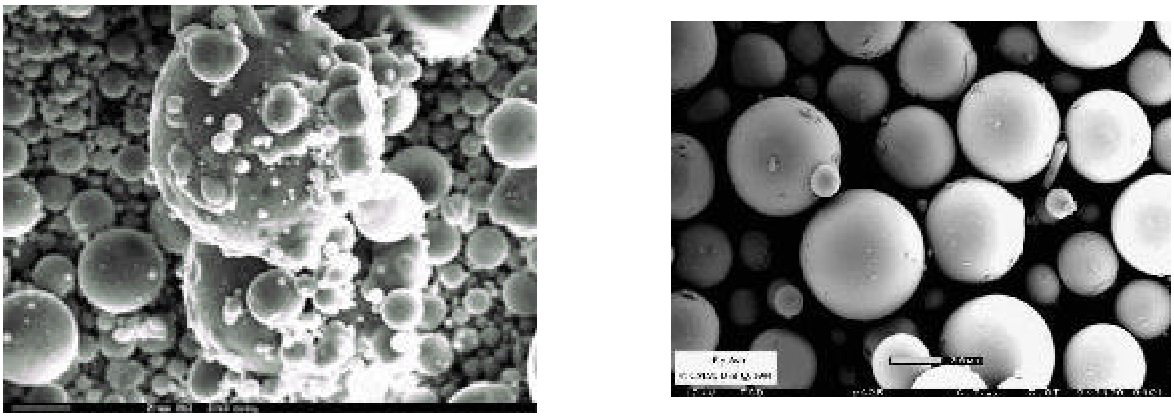


Figura 1 – Ceneri leggere di carbone osservate al SEM

In Figura 2 è riportata una tipica distribuzione granulometrica di una cenere leggera determinata mediante granulometro laser.

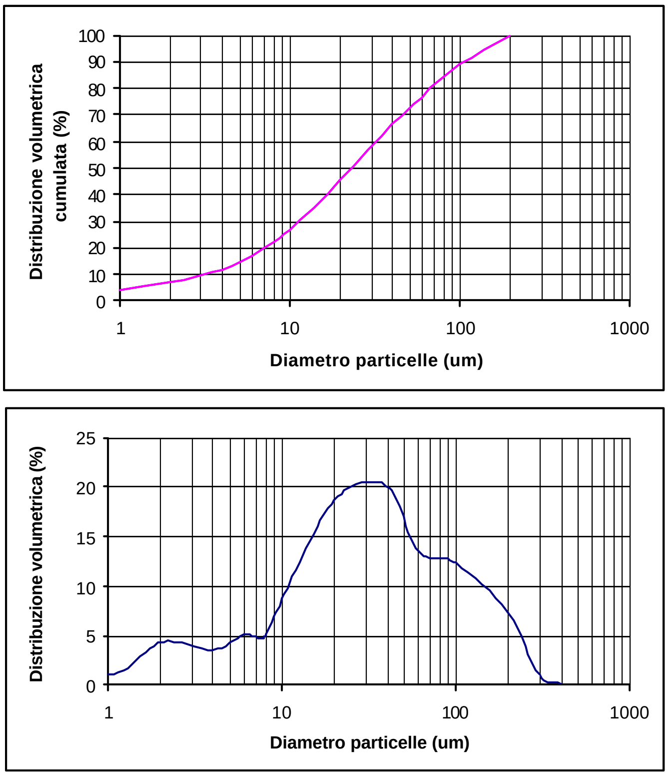


Figura 2 – Distribuzione granulometrica di un campione tipico di ceneri leggere di carbone

La composizione chimica delle ceneri leggere, di cui in Tabella 1 vengono riportati i tipici range di variazione dei componenti *macro*, è prevalentemente silico-alluminosa, assimilabile a quella di una pozzolana naturale. Ad esse è paragonabile anche dal punto di vista microstrutturale, essendo costituita prevalentemente (per più del 70%) da particelle di natura amorfa o vetrosa prodotte dal brusco raffreddamento che ha impedito la riorganizzazione del reticolo cristallino all'interno dei granuli.

Tabella 1 - Contenuto percentuale dei principali componenti delle ceneri e confronto con le pozzolane naturali

Elemento Componente	Ceneri da Carbone Polacco	Ceneri da Carbone Sudafricano	Ceneri da Carbone Americano	Pozzolana Romana	Pozzolana Napoletana
Si	18,7÷23,4	16,0÷20,9	19,0÷22,9	21÷22	25÷31
Al	10,6÷13,2	14,8÷18,5	12,4÷16,8	8÷12	9÷16
Fe	5,0÷10,0	1,5÷3,8	1,7÷8,7	4÷8	3÷4
Ca	3,6÷7,1	1,1÷6,5	0,7÷4,2	6÷7	2÷3
Mg	1,8÷3,0	0,3÷1,1	0,1÷1,0	0,5÷2	0,5÷1
S	2,0÷4,0	0,2÷0,4	0,2÷1,1	-	-
K	0,8÷2,5	0,4÷0,9	0,5÷2,2	1÷2,5	2,5÷7
Na	0,4÷0,7	0,1÷0,4	0,1÷0,7	0,6÷0,8	1,2÷3,2
Ti	0,4÷0,6	0,6÷1,0	0,6÷1,0	-	-
P	0,1÷0,3	0,2÷1,0	0,1÷0,6	-	-
Incombusti	4÷6	5÷8	5÷8	-	-

La massa volumica *reale* delle ceneri leggere oscilla tra 2100 e 2400 g/cm^3, mentre quella *apparente* è generalmente compresa tra 600 e 800 g/cm^3.

Nella composizione delle ceneri leggere di carbone si trovano anche tracce di altri elementi, in quantità dell'ordine dei ppm (mg/kg), generalmente indicati come *micro-componenti* o *componenti in tracce*.

Al riguardo, le successive Tabelle 2 e 3 presentano rispettivamente i range di variazione dei principali elementi costitutivi il carbone ed i suoi sottoprodotti di combustione (ceneri pesanti, ceneri leggere e particolato solido emesso al camino) estratti dalla bibliografia.

Dalle precedenti tabelle è anche possibile osservare come le ceneri pesanti, o di fondo caldaia, hanno composizione chimica simile a quella delle ceneri leggere. Differente è invece la loro granulometria; esse formano infatti grossi accumuli fusi sulle superfici interne della caldaia da cui colano e si distaccano ricadendo sul fondo della stessa. Estratte a secco mediante opportuni nastri trasportatori vengono successivamente macinate ad una dimensione assimilabile alle stesse ceneri leggere. In virtù di quanto detto, i granuli di ceneri pesanti non presentano la tipica forma sferoidale delle ceneri leggere e, in conseguenza del più lento processo di raffreddamento, hanno un maggior contenuto di fase cristallina.

Tabella 2 - Confronto tra le concentrazioni elementari nel carbone, nel suolo e nella crosta terrestre [*Reported data IEA 1992*]

Element	Coal		Soil	Earth's crust
	Typical concentration	Range		
Macro-elements, concentrations in %				
Cl	0.1	0.005 ÷ 0.2	0.01	0.016
P	0.015	0.001 ÷ 0.3	0.05	0.1
Ti	0.06	0.001 ÷ 0.2	0.3	0.44
Trace and micro-elements, concentrations in $mg.kg^{-1}$				
As	10	0.5 ÷ 80	7	1
B	50	5 ÷ 400	30	10
Ba	200	20 ÷ 1000	500	425
Be	2	0.1 ÷ 15	1	3
Br	20	0.5 ÷ 90	10	0.75
Cd	0.5	0.1 ÷ 3	0.6	0.2
Ce	20	2 ÷ 70		60
Co	5	0.5 ÷ 30	10	25
Cr	20	0.5 ÷ 60	55	100
Cs	1	0.3 ÷ 5	4	3
Cu	15	0.5 ÷ 50	25	55
Eu	0.5	0.1 ÷ 2		1.2
F	150	20 ÷ 500	300	544
Ge	5	0.5 ÷ 50	1	1.5
Hf	1	0.4 ÷ 5		3
Hg	0.1	0.02 ÷ 1	0.1	0.08
I	5	0.5 ÷ 15	7	0.25
La	10	1 ÷ 40		30
Mn	70	5 ÷ 300	550	950
Mo	3	0.1 ÷ 10	1	1.5
Ni	20	0.5 ÷ 50	20	75
Pb	40	2 ÷ 80	20	13
Rb	15	2 ÷ 50		90
Sb	1	0.05 ÷ 10	0.7	0.2
Sc	4	1 ÷ 10	9	22
Se	1	0.2 ÷ 10	0.4	0.05
Sm	2	0.5 ÷ 6		6
Sr	200	15 ÷ 500	240	375
Th	4	0.5 ÷ 10	9	7.2
Tl	<1		0.2	0.5
U	2	0.5 ÷ 10	2.7	1.8
V	40	2 ÷ 100	80	135
W	1	0.5 ÷ 5		1.5
Zn	50	5 ÷ 300	70	70

Tabella 3 – Composizione elementare media nel carbone e nelle ceneri

(Tabella tratta da “Status Report on Healt Issues Associated with Pulvertised Fuel Ash and Fly Dust” KEMA (NL) 1998)

	Coal	Bottom ash	Pulverised fly ash	Fly dust
Macro-elements, concentrations in %				
Al	1.52 ± 0.53	13.8 ± 4.8	13.8 ± 4.8	13.8
C	73.3 ± 2.5	2.2	4.9 ± 2.3	
Ca	0.26 ± 0.08	2.4 ± 0.7	2.4 ± 0.7	2.4
Cl	0.05 ± 0.02	0.003 ± 0.002	0.003 ± 0.002	0.1
Fe	0.46 ± 0.22	4.2 ± 2.0	4.2 ± 2.0	4.2
K	0.15 ± 0.08	1.3 ± 0.8	1.3 ± 0.8	1.3
Mg	0.09 ± 0.03	0.8 ± 0.2	0.8 ± 0.2	0.8
Na	0.04 ± 0.02	0.3 ± 0.13	0.3 ± 0.2	0.5
S	0.67 ± 0.007	0.12 ± 0.001	0.13 ± 0.001	
P	0.03 ± 0.12	0.10 ± 0.5	0.2 ± 1.1	0.7
Si	2.54 ± 0.61	23.1 ± 5.5	23.1 ± 5.5	23.1
Ti	0.08 ± 0.03	0.8 ± 0.2	0.8 ± 0.2	0.8
Trace and micro-elements, concentrations in mg.kg-1				
As	4.0 ± 2.0	2.6 ± 1.4	36 ± 19	217
B	47.5 ± 19	155 ± 62	259 ± 103	432
Ba	165 ± 93	1166 ± 655	1503 ± 844	2693
Be	2.0 ± 3.1	13 ± 21	18 ± 28	29
Br	5.4 ± 5.0	<0.5 ± 0.5	4 ± 4	58
Cd	0.10 ± 0.07	0.3 ± 0.2	0.9 ± 0.6	7
Ce	19.6 ± 5.7	174 ± 50	178 ± 52	178
Co	5.2 ± 1.6	32 ± 10	47 ± 15	110
Cr	16.4 ± 4.7	149 ± 43	149 ± 43	234
Cs	0.9 ± 0.44	8 ± 4	8 ± 4	8
Cu	12.6 ± 6	55 ± 25	115 ± 51	273
Eu	0.4 ± 0.14	3.4 ± 1.2	3.4 ± 1.2	3
F	100 ± 51	68 ± 35	145 ± 74	1360
Ge	1.7 ± 0.4	7 ± 2	15 ± 3	120
Hf	1.1 ± 0.4	10 ± 3	10 ± 3	10
Hg	0.10 ± 0.10	0.07 ± 0.06	0.5 ± 0.5	2
I	2.4 ± 2.3	<0.7 ± 0.6	0.7 ± 0.6	
La	9.3 ± 2.1	84 ± 19	84 ± 19	84
Mn	38.8 ± 23	353 ± 214	353 ± 214	588
Mo	2.4 ± 1.4	10 ± 6	22 ± 13	95
Ni	10.0 ± 4.3	67 ± 29	91 ± 39	291
Pb	6.5 ± 3.1	33 ± 16	59 ± 29	274
Rb	10.1 ± 6	92 ± 58	92 ± 58	92
Sb	0.6 ± 0.26	1.2 ± 0.6	5 ± 2	29
Sc	3.4 ± 0.8	30 ± 7	30 ± 7	30
Se	2.6 ± 1.0	<0.23 ± 0.09	15 ± 6	314
Sn	1.4		13	
Sm	2 ± 0.4	16 ± 4	16 ± 1	16
Sr	135.7 ± 48	1234 ± 433	1234 ± 433	1234
Te	<1	9	9	9
Th	3.2 ± 0.9	29 ± 8	29 ± 8	29
Tl	<1.0	<3	<9	41
U	1.3 ± 0.5	8 ± 3	12 ± 5	34
V	25.4 ± 9	161 ± 55	231 ± 79	699
W	0.8 ± 0.6	5 ± 4	7 ± 5	22
Zn	17.9 ± 9	81 ± 40	163 ± 80	905

2.2. Potenzialità di riutilizzo

Le caratteristiche chimiche e fisiche delle ceneri di carbone le rendono idonee come sostitutivo di materiali naturali per una pluralità di impieghi.

Esse trovano utilizzo consolidato quale materia prima in numerosi processi industriali, quali la produzione di cemento, di calcestruzzo, di aggregati artificiali e manufatti prefabbricati, di laterizi.

Sono inoltre largamente utilizzate nella realizzazione di infrastrutture viarie e per interventi sul territorio (realizzazione di sottofondi stradali e ferroviari, realizzazione di rilevati strutturali e di riempimenti per la riqualificazione di aree morfologicamente degradate).

In relazione all'ampia gamma di possibili destinazioni d'uso delle ceneri, a titolo esemplificativo, nella successiva Tabella 4 viene riportato un elenco dei principali settori di impiego dei sottoprodotti della combustione del carbone (al fianco delle ceneri vengono riportati anche i gessi FGD), affiancati alle corrispondenti materie prime sostituite.

Nei successivi capitoli del presente rapporto viene presentato un più approfondito esame dei principali aspetti legislativi, normativi e tecnici che regolamentano e rendono le ceneri competitive in queste applicazioni.

Tabella 4 - Coal Combustion By-Products: Applications and Competing Materials [1]

APPLICATION	FLY ASH	BOTTOM ASH	FGD MATERIAL	COMPETING MATERIALS
Concrete & Concrete Products	X	X		Cement, Silica Fume, Ground Blast Furnace Slag
Cement Manufacture	X	X	X	Clay, Soil, Shale, Gypsum
Road Base and Subgrade	X	X	X	Cement, Lime, Aggregate
Road Surfacing	X	X		Cement, Lime, Aggregate
Soil / Bank Stabilization	X	X	X	Cement, Lime, Aggregate
Structural Fill (Contained Under a Footprint)	X			Sand, Gravel, Soil, Aggregate
Structural Fill (Not Contained Under a Footprint)	X	X		Sand, Gravel, Soil
Backfill	X	X	X	Soil, Sand, Gravel, Cement
Flowable Fill	X	X		Soil, Sand, Gravel, Cement
Asphalt Mineral Filler	X	X		Sand
Asphaltic Concrete Aggregate	X	X		Sand, gravel, Aggregate
Asphalt Blotter Matter		X		Sand
Building Products, Blocks	X	X		Cement, Aggregate
Bricks	X	X	X	Clay, Sand, Cement
Clay Bricks (Grog)		X		Aggregate
Autoclaved Cellular Concrete	X			Sand
Wallboard (Sheetrock)			X	Natural Gypsum
Roofing Material, Shingles	X	X		Alternate Filler Materials, Sand
Plastics	X			Alternate Filler Materials
Paint	X			Alternate Filler Materials
Grouts	X			Cement, Lime, Sand
Carpet Backing	X			Alternate Filler Materials
Artificial Reefs	X	X		Oyster Shell, Rock
Roadway Deicing Material		X		Sand, Salt
Sand Blasting Grit		X		Sand
Metal Alloys	X			Aluminum, Alternate Filler Materials
Waste Stabilization & Solidification	X			Cement, Lime, Cement Kiln Dust, Lime Kiln Dust
Mine Fill		X		Soil
Fertilizers & Soil Amendments		X	X	Natural Gypsum

[1] Tratto da Western Region Ash Group, http:/www.wrashg.org/westuse.htm.

2.3. Quadro legislativo

Il testo base della legislazione italiana sui rifiuti è rappresentato dal “Decreto Ronchi” (decreto legislativo 5 febbraio 97, n° 22 pubblicato sul *Supplemento Ordinario della G.U. n. 33 del 15/2/1997*) e successive modifiche (D.ti 389/97 e 4265/98). Esso è conforme a quanto previsto in ambito europeo in termini di classificazione e gestione dei rifiuti, avendo recepito le Direttive Comunitarie 91/456/CEE, 91/689/CEE e 94/62/CEE in materia di produzione, deposito e smaltimento dei rifiuti.

Il "Decreto Ronchi" modifica, rispetto alla precedente legislazione basata sulla Legge 915/82, la gestione dei rifiuti, cambiando classificazioni, codici e terminologie usate, armonizzandole con quelle del resto d’Europa.

I rifiuti sono classificati, secondo la loro origine, in "rifiuti urbani" e "rifiuti speciali" e tra questi, guardando alle loro caratteristiche, in rifiuti "pericolosi" e "non pericolosi".

I rifiuti vengono individuati in base ad un codice riportato nell’elenco in allegato C al Decreto. L’elenco è il cosiddetto Catalogo Europeo dei Rifiuti (abbr. CER), comprendente tutti i tipi di rifiuti, sia che siano destinati allo smaltimento che al recupero.

Il CER costituisce un elenco soggetto a periodica revisione ed oggetto di eventuali modifiche laddove necessario, in funzione del progresso tecnico-scientifico. Esso è costituito da 20 classi di rifiuto, identificate con una sequenza numerica di sei cifre di cui le prime due rappresentano la classe di appartenenza del rifiuto, le due successive la sottoclasse del rifiuto, le ultime due l’identificazione vera e propria del rifiuto.

In riferimento alle ceneri di carbone il CER indica i seguenti codici identificativi:

10 00 00 Rifiuti inorganici provenienti da processi termici

10 01 00 rifiuti di centrali termiche ed altri impianti termici

10 01 01 ceneri pesanti
10 01 02 ceneri leggere

Le ceneri vengono classificate come *rifiuti speciali* ***non pericolosi*** non risultando riportate nel successivo Allegato D al Decreto i cui vengono indicati, elencandoli, i soli rifiuti classificati come pericolosi.

In relazione alle potenzialità di riutilizzo dei rifiuti, il Decreto Ronchi prevede la possibilità di applicare:

1. una procedura ordinaria, sottoposta ad autorizzazione regionale, prevista dagli art. 27 e 28;

ovvero, nel caso di specifici settori di riutilizzo la cui compatibilità ambientale, oltre che tecnologica, appare conclamata,

2. una procedura semplificata, che prevede semplicemente una comunicazione alla provincia, secondo quanto previsto dall'art. 33 e attuata dal Decreto Ministeriale 5 febbraio 1998.

Il D.M. 5/2/98 individua quindi le attività di recupero dei rifiuti non pericolosi soggette alle procedure autorizzative semplificate, sia come materia prima (nell'Allegato 1 al decreto) sia come combustibile (nell'Allegato 2 allo stesso).

Per le ceneri da carbone esso individua i seguenti settori di utilizzo[2]:

a) produzione di cementi, calcestruzzi e manufatti prefabbricati;
b) produzione di laterizi;
c) produzione di aggregati artificiali.

Si riporta di seguito l'estratto del decreto DM 2/5/98:

13.1 **Tipologia:** ceneri dalla combustione di carbone e lignite, anche additivati con calcare e da cocombustione con esclusione dei rifiuti urbani ed assimilati tal quali [100101] [100102] [100103].

13.1.1 **Provenienza:** centrali termoelettriche.

13.1.2 **Caratteristiche del rifiuto:** è generalmente composto dall' 80% circa di ceneri volanti e dal 20% circa di ceneri pesanti; costituito da silicati complessi di alluminio, calcio e ferro, sostanza carboniosa incombusta (2 ÷ 10%); PCDD in concentrazione non superiore a 2,5 ppb, PCB, PCT < 25 ppm.

13.1.3 **Attività di recupero:**
a) cementifici [R5];
b) produzione di conglomerati cementizi: le ceneri vengono miscelate agli altri materiali, a freddo, e nella fase di preparazione del manufatto finale [R5];
c) industria dei laterizi, industria della produzione di argilla espansa [R5].

13.1.4 **Caratteristiche delle materie prime e/o dei prodotti ottenuti:**
a) cemento nelle forme usualmente commercializzate;
b) conglomerati cementizi nelle forme usualmente commercializzate;
c) laterizi e argilla espansa nelle forme usualmente commercializzate.

[2] E' interessante notare come il precedente DM 5/9/94 "Attuazione degli artt. 2 e 5 del DL 8/7/94 n° 438 recante disposizioni in materia di riutilizzo dei residui ..." riportasse già in riferimento alle ceneri di carbone (p.to 13 dell'All.3) la ulteriore destinazione:

d) rilevati e sottofondi stradali: il test di cessione deve rientrare nei limiti di Tab. A della L 319/76 e succ. mod. e int., fatte salve le prescrizioni vigenti a tutela delle falde acquifere.

Tale applicazione, nonostante sia ampiamente diffusa all'estero ad attestata dalla relativa legislazione, come sintetizzato nel rapporto, è stata eliminata dal successivo DM 2/5/98.

2.4. Quadro tecnico normativo

2.4.1. Situazione in Europa

L'attività normativa tecnica internazionale sul riutilizzo delle ceneri di carbone riguarda prevalentemente il loro impiego nella produzione di **cementi di miscela** e di **calcestruzzi**, in qualità di aggiunte pozzolaniche (normalmente indicate come aggiunte di *tipo II*).

I più importanti standard, italiani ed europei, per la definizione delle modalità di riutilizzo ed il controllo di qualità delle ceneri leggere di carbone nella produzione di cementi e calcestruzzi sono i seguenti:

UNI - ENV	**197/1**	"Cemento - Composizione, specificazioni e criteri di conformità";
UNI - ENV	**206**	"Calcestruzzo - Prestazioni, produzione e criteri di conformità".
UNI - EN	**450**	"Ceneri leggere per calcestruzzi";

La norma **ENV 197/1** classifica i tipi di cemento ed i loro possibili intervalli di composizione, definisce i loro requisiti chimico-fisici e le classi di resistenza, indicando inoltre i criteri per il loro controllo di qualità.

I materiali di aggiunta consentiti per l'ottenimento d cementi compositi ed i relativi tenori sono riportati in Tabella 5.

Le ceneri di carbone "siliciche" sono presenti nella formulazione del *cemento Portland alle ceneri* (tipo II-V), del *cemento Portland composito* (tipo II-M) e del *cemento pozzolanico* (tipo V) con percentuali in peso che vanno dal 6 al 55%. Per esse vengono indicati i seguenti requisiti di controllo qualità: perdita al fuoco ≤ 5% in peso, CaO reattiva ≤ 5% in peso e SiO_2 reattiva ≥ 25% in peso.

La UNI - ENV 197/1 è vigente in Italia, essendo stata adottata come norma tecnica di riferimento dal D. MICA 13 sett 1993 sulla produzione ed il controllo dei cementi.

Il pre-standard **UNI-ENV 206** prescrive i requisiti tecnici per il calcestruzzo (materiali costituenti, composizione, proprietà e verifiche di produzione, trasporto, posa in opera e maturazione). Esso distingue i calcestruzzi in base alle classi di esposizione ambientale attese in esercizio (clima secco o umido, con gelo, marino, chimicamente aggressivo, ecc.) e per ciascuna classe prescrive un contenuto minimo di cemento ed un rapporto massimo acqua/cemento ammessi per garantire la durabilità del manufatto finale.

La precedente norma *sperimentale* consente l'utilizzo nella produzioni di calcestruzzi di ceneri conformi ai requisiti della UNI-EN 450, di seguito brevemente descritta, introducendo per esse un fattore di equivalenza "k" rispetto al cemento.

In base al concetto di fattore di equivalenza, il tenore di "legante totale" nel calcestruzzo è pari a "[cemento] + k · [cenere]" e viene consentito di assumere un valore di k = 0,2 se le ceneri vengono utilizzate al fianco di un cemento Portland di classe 32,5 e di k = 0,4 se esse affiancano invece un cemento Portland di classe 42,5 o superiore. Il tenore massimo di cemento sostituibile è inoltre indicato dalla relazione $\Delta c \leq k\,(c_{min} - 200)$ - in kg - essendo c_{min} il tenore minimo di legante prescritto dallo standard. Il rapporto cenere/cemento ≤ 0,33 limita inoltre il tenore massimo di cenere consentito in qualità di aggiunta attiva (pozzolanica).

La UNI ENV 206 è una norma sperimentale ed i singoli paesi europei sono chiamati ad applicarla al fine di verificarne la validità. Vigente in Italia resta tuttavia la UNI 9859 che recepisce una precedente versione della stessa ENV 206 (risalente al 1990), di cui conserva quindi l'impostazione, ma in cui viene esplicitamente assegnato (Prospetto III nota 2 pag. 11) un valore k=0 al fattore di equivalenza delle ceneri rispetto al cemento. All'opposto, paesi come la Francia hanno fissato, in funzione dei risultati della prova di pozzolanicità delle ceneri, valori di k che possono arrivare fino a 0.6.

La norma **UNI-EN 450** indica i requisiti chimico-fisici e le modalità per il controllo di qualità delle ceneri leggere utilizzate come aggiunta pozzolanica per la produzione di calcestruzzi gettati in opera o preconfezionati. Questi requisiti sono sinteticamente riportati in Tabella 6. Le principali caratteristiche chimiche richiamate sono la *perdita al fuoco (LOI)* ed il tenore di *cloruri*, *solfati* e *calce libera*. Le proprità fisiche da controllare sono invece la *finezza*, l'*indice di attività pozzolanica*, la *stabilità dimensionale* nelle malte e la *densità*.

Tabella 5 - Tipi di cemento e loro composizione - Percentuali in massa (UNI ENV 197/1)

Tipo di cemento	Denominazione	Sigla	Clinker K	Loppa d'alto-forno granul. S	Micro-silice D	Pozzolana		**Cenere volante**		Scisto calcinato T	Calcare L	Costituenti secondari
						naturale P	industriale Q	**silicica Cs**	calcica Cc			
I	Cemento Portland	I	95-100	-	-	-	-	-	-	-	-	0-5
II	Cemento Portland	II/A-S	80-94	6-20	-	-	-	-	-	-	-	0-5
	alla loppa	II/B-S	65-79	21-35	-	-	-	-	-	-	-	0-5
	Cemento Port. alla microsilice	II/A-D	90-94	-	6-10	-	-	-	-	-	-	0-5
	Cemento Portland alla pozzolana	II/A-P	80-94	-	-	6-20	-	-	-	-	-	0-5
		II/B-P	65-79	-	-	21-35	-	-	-	-	-	0-5
		II/A-Q	80-94	-	-	-	6-20	-	-	-	-	0-5
		II/B-Q	65-79	-	-	-	21-35	-	-	-	-	0-5
	Cemento Portland alle ceneri volanti	II/A-V	80-94	-	-	-	-	**6-20**	-	-	-	0-5
		II/B-V	65-79	-	-	-	-	**21-35**	-	-	-	0-5
		II/A-W	80-94	-	-	-	-	-	6-20	-	-	0-5
		II/B-W	65-79	-	-	-	-	-	21-35	-	-	0-5
	Cemento Portland allo	II/A-T	80-94	-	-	-	-	-	-	6-20	-	0-5
	scisto calcinato	II/B-T	65-79	-	-	-	-	-	-	21-35	-	0-5
	Cemento Portland	II/A-L	80-94	-	-	-	-	-	-	-	6-20	0-5
	al calcare	II/B-L	65-79	-	-	-	-	-	-	-	21-35	0-5
	Cemento Portland	II/A-M	80-94	<------------------------------ **6-20** ----------------------------->								
	composito	II/B-M	65-79	<------------------------------ **21-35** ----------------------------->								
III	Cemento d'altoforno	III/A	35-64	36-65	-	-	-	-	-	-	-	0-5
		III/B	20-34	66-80	-	-	-	-	-	-	-	0-5
		III/C	5-19	81-95	-	-	-	-	-	-	-	0-5
IV	Cemento pozzolanico	IV/A	65-89	-	<---------- **11-35** -------->				-	-	-	0-5
		IV/B	45-64	-	<---------- **36-55** -------->				-	-	-	0-5
V	Cemento composito	V/A	40-64	18-30	-	<------- **18-30** ----->			-	-	-	0-5
		V/B	20-39	31-50	-	<------- **31-50** ----->			--	-	-	0-5

Tabella 6 - Requisiti di controllo qualità delle ceneri secondo la UNI EN 450

Caratteristiche chimico-fisiche	Requisito di accettazione		Procedura di prova	Frequenza di controllo
	Valore caratteristico	Limite per maggior difetto		
Perdita al fuoco (%)	≤ 5.0 / 7.0[1]	+ 2.0	EN 196-2	giornaliera
Cloruri (Cl^-) (%)	≤ 0.10	+ 0.01	EN 196-21	mensile
Solfati (SO_3) (%)	≤ 3.0	+ 0.5	EN 196-2	mensile
Calce libera (%)	≤ 1.0 ≤ 2.5[2]	+ 0.1	EN 451-1	settimanale
Stabilità Le Chatelier (mm) (CaO_{lib}=1¸2.5%)	≤ 10.0	+ 1.0	EN 196-3	settimanale, se necessaria
Finezza (%) **(trattenuto a 45 mm)**	≤ 40.0	+ 5.0	EN 451-2	giornaliera
Uniformità di finezza (%)	Valore medio ± 5.0	-		giornaliera
Indice di attività pozzolanica (%)	≥ 75.0 a 28 gg ≥ 85.0 a 90 gg	- 5.0	EN 450 EN 196-1	bisettimanale
Densità (Kg/m^3)	valore medio ± 150	-	UNI 8529/13 EN 196-6	mensile

(1) il limite del 7% può essere accettato su base nazionale.
(2) limite ammesso se soddisfatta la prova di stabilità Le Chatelier

2.4.2. Situazione negli USA

A titolo esemplificativo della situazione normativa internazionale, si riporta il caso degli Stati Uniti. I principali Standard americani rilevanti ai fini della caratterizzazione ed il riutilizzo delle ceneri di carbone sono i seguenti:

ASTM C 311 Samplingand Testing Fly Ash or natural Pozzolans for Use as a Mineral Admixtures in Portland Cement Concrete

ASTM C 618 Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixtures in Portland Cement Concrete

ASTM C 593 Fly Ash and Other Pozzolans for Use with Lime

ASTM D 5239 Standard Parctice for Characterising Fly Ash for Use in Soil Stabilisation

ASTM PS 23-95 Guide for the Use of Coal Combustion Fly Ash in Structural Fills

Di particolare interesse ai fini del presente studio appare quest'ultimo standard, riportato in Allegato 3 al presente Rapporto.
Nello standard ASTM PS 23-95 vengono considerate le modalità di progettazione e di realizzazione dei rilevati strutturali a base di ceneri di carbone ed esso suggerisce criteri e procedure idonei per la valutazione dei principali aspetti ingegneristici, economici ed ambientali correlati a tale forma di riutilizzo. Ad esso verrà fatto ulteriore riferimento nel successivo § 3.2.3. relativo alla analisi degli aspetti ambientali legati all'impiego in campo geotecnico delle ceneri leggere.

Al fianco dei precedenti Standard, ulteriori linee guida tecniche finalizzate a promuovere i benefici tecnici economici ed ambientali legati all'impiego delle ceneri di carbone in campo geotecnico (strati di base, rilevati strutturali, riempimenti) sono state elaborate dai singoli Stati membri e da singole associazioni. Più di 20 Stati negli USA hanno elaborato specifiche sull'uso delle ceneri per impieghi geotecnici; fra questi : Colorado, Delaware, Florida, Georgia, Illinois, Indiana, Kansas, Kentuky, Maryland, Massachussets, Michigan, Minnesota, Nebraska, New Hampshire, New Mexico, North Carolina, Ohio, Texas, Washington, West Virginia e Wisconsin[3].

Fra le numerose associazioni, in particolare l'EPA (U. S. Environmental Protection Agency) ha promosso l'impiego delle ceneri leggere per la realizzazione di materiali da costruzione (cementi e calcestruzzi) ed in campo geotecnico (riempimenti) inserendoli nei CPG: Comprehensive Procurement Guidelines, strumento chiave del programma governativo "buy-recycled" mirato a promuovere l'utilizzo dei rifiuti ambientalmente e tecnicamente recuperabili, e nei RMANs: EPA's Recovered Materials Advisory Notices, in cui vengono indicati i tenori raccomandati di rifiuto da utilizzare nella produzione dei materiali e nelle applicazioni selezionate nelle precedenti CPG.

In particolare, in relazione alla posizione assunta dall'EPA, all'indirizzo: www.epa.gov/cps/products/flow-fil.htm si legge, in riferimento all'impiego delle ceneri nelle miscele fluide per riempimenti,:

> Flowable fill is commonly used as an economical fill or backfill in road construction. It is usually a mixture of coal fly ash, water, a coarse aggregate (such as sand), and portland cement. Flowable fill

[3] Da http://www.epa.gov/cpg/products/flow-ast.htm

> can take the place of concrete, compacted soils, or sand commonly used to fill around pipes or void areas. Other applications include filling in bridge abutments, foundation subbases, or abandoned man holes and wells. Flowable fill can help put significant quantities of coal fly ash … back to good use. **EPA recommends that procuring agencies use flowable fill containing coal fly ash** … for backfill and other fill applications.

Un ulteriore documento tecnico di riferimento negli USA è rappresentato dal Rapporto FHWA-SA-94-081 **"Fly Ash Facts for Highway Engineers"** pubblicato nell'Agosto 1995 dall'U. S. Department of Trasportation - Federal Highway Administration, riportato in Allegato XXXX al presente studio. Come riportato nella prefazione al Rapporto, il suo obiettivo è di *fornire ai potenziali utilizzatori dei sottoprodotti della combustione termoelettrica del carbone informazioni tecniche in relazione alle loro applicazioni ingegneristiche e di promuoverne l'impiego in condizioni tecnicamente idonee, commercialmente competitive ed ambientalmente sicure*.
Gli impieghi indicati sono, con evidenza, proprio quelli relativi alle realizzazione di strati di fondazione e riempimenti strutturali, oggetto del presente studio.

2.5. Dati di produzione e destinazione

2.5.1 La situazione in Europa

Nell'Unione Europea sono state prodotti nel 1999 circa 55 milioni di tonnellate di sottoprodotti della combustione del carbone per produzione termoelettrica.
Di questi, oltre 37 Mton, pari a quasi il 70%, sono costituiti da ceneri leggere.
Esse sono state utilizzate in un elevato numero di settori, soprattutto nell'industria delle costruzioni, per una frazione pari al 48% del loro totale.
Le applicazioni principali delle ceneri leggere hanno riguardato la loro aggiunta tal quale nella produzione di calcestruzzi (~30%) e cementi di miscela (~10%), il loro impiego come materia prima per la produzione di cemento di Portland (~20%) e come aggregato o legante nella costruzione di strade (~22%).
Nella maggior parte dei casi esse hanno sostituito materie prime naturali, con conseguenti notevoli benefici ambientale legati alla riduzione dell'attività di estrazione e trattamento di queste risorse.

Nella successiva Tabella 7 vengono dettagliati i valori di produzione e destinazione dei differenti sottoprodotti termoelettrici (indicati con la sigla CCBs Coal Combustion Products) elaborati dall'ECOBA (European Association for Use of the By-Products of Coal-Fired Power-Stations e.V.).
I dati tabellati vengono confrontati nei diagrammi delle successive Figure 3 e 4.

Tabella 7 - Produzione ed Utilizzo di Residui termoelettrici nel 1999 in Europa
(in migliaia di tonnellate)*

		Fly Ash	Bottom Ash	Boiler Slag	FBC - Ashes	Other	SDA - Product	FGD- Gypsum		
		1	2	3	4	5	6	7		
CCP Production		37.144	5.622	2.417	985	240	520	7.574		
Subtotal 1 - 5						**46.408**				
Subtotal 6 - 7								**8.094**		
Total 1 - 7								**54.502**		
CCP Utilization									**Total**	**%**
Cement raw material	1	3.736	54						3.790	6,8
Blended cement	2	1.930			7				1.937	3,5
Concrete addition	3	5.436	20	162	30				5.648	10,2
Aerated concrete blocks	4	666	70						736	1,3
Non-aerated concrete blocks	5	593	1.233						1.826	3,3
Lightweight aggregate	6	238	80				5		323	0,6
Bricks + ceramics	7	68							68	0,1
Grouting	8	521		156					677	1,2
Asphalt filler	9	186			50				236	0,4
Subgrade stabilisation	10	330	31						361	0,7
Pavement base course	11	206	326	1.245					1.777	3,2
General engineering fill	12	1.299	374				27		1.700	3,1
Structural fill	13	1.386	183						1.569	2,8
Soil amendment	14	1					84		85	0,2
Infill	15	1.378			356		320		2.054	3,7
Blasting grit	16			732					732	1,3
Plant nutrition	17			35			35		70	0,1
Set retarder for cement	18							471	471	0,8
Projection plaster	19							621	621	1,1
Plaster boards	20							4.035	4.035	7,3
Gypsum blocks	21							243	243	0,4
Self levelling floor screeds	22							1.252	1.252	2,3
Other uses	23	195	129	87	2	240		0	653	1,2
Landfill, Reclamation, Restoration	24	15.425	2.070	0	393		37	424	18.349	33,0
Temporary stockpile	25	717	31	0	0		0	445	1.193	2,1
Disposal	26	3.806	1.057	0	147		12	94	5.116	9,2
Total utilization 1-23	27	18.169	2.500	2.417	445	240	471	6.622	30.864	55,6
Utilization rate in %	28	48	44	100	45	100	91	87		
Average utilization rate in %	29							56		
Total utilization 1-24	30	33.594	4.570	2.417	838	240	508	7.046	49.213	88,6
Utilization rate in %	31	88	81	100	85	100	98	93		
Average utilization rate in %	32							90		
Reuse of stockpiled CCPs	33	973	36	0	0	0	0	11	1.020	1,8
Total production 1-26 incl. reuse	34	38.117	5.658	2.417	985	240	520	7.585	55.522	100,0

[* dati estratti da www.ecoba.com]

Definizione dei termini utilizzati nella precedente Tabella 7:

Cement raw material	Ash which is fed into a cement kiln as a constituent of the raw mix in the production of portland cement clinker
Blended cement	A mixture of cement and other cementitious material (eg. Ash)
Concrete addition	An inert or cementitious additive to concrete which improves the performance of the concrete
Aerated concrete	A low density concrete building block which contains large quantities of entrained air/gas
Non aerated block	A block produced from a cementitious mix
Lightweight aggregate	Aggregate having a density of no more loose bulk density than 1200 kg/m^3
Bricks and ceramic	Fired clay ware building products /eg. Bricks, pipes and tiles)
Grouting	The injection of a fluid cementitious mix to fill voids or to improve the strength or permeability of rocks and soils
Asphalt filler	Ash used as a fill in the production of asphalt or to improve strength
Subgrade stabilisation	Ash used to improve the bearing capacity of solis underlying road constrution
Pavement base course	foundation material in road construction overlying the sub base and supporting the pavement
General engineering fill	Ash used to construct an embankment to support a road, railway or other structure (eg. Structural enbankment fill)
Structural fill	Ash used in application in which its shear strength is important (eg. Behind retaining walls and as a fill in reinforced earth)
Soil amendment	Ash used to modify soil to improve its performance
Infill	Ash used to fill enclosed voids, mine shats, subsurface mine working
Restoration	Ash used for the profiling of land as part of a restoration plan; ash used as, or part of a 2soil recipe" which is used for restoration purposes
Reclamantion	Infilling of voids with to sole purpose of returning land to beneficial us (eg. Man made excavations or contaminated land)
Landfill	Infilling of a man or natural void or depression or the reprofiling of existing land (eg. Worked out abandoned quarries, avlley for beneficial use or as a disposal facility; filler for open cast mines, quarries and pits)
Disposal	Ash which is deposited in or onto a licenced waste disposal facility

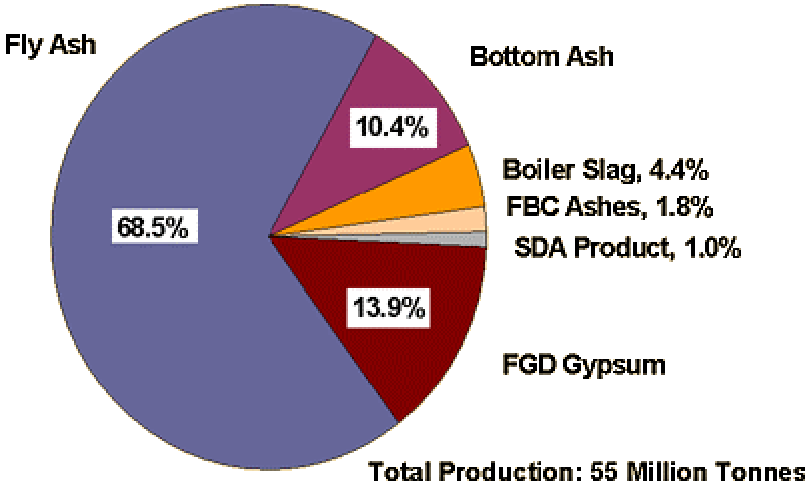


Figura 3 - Production of CCPs in Europe (EU 15) in 1999

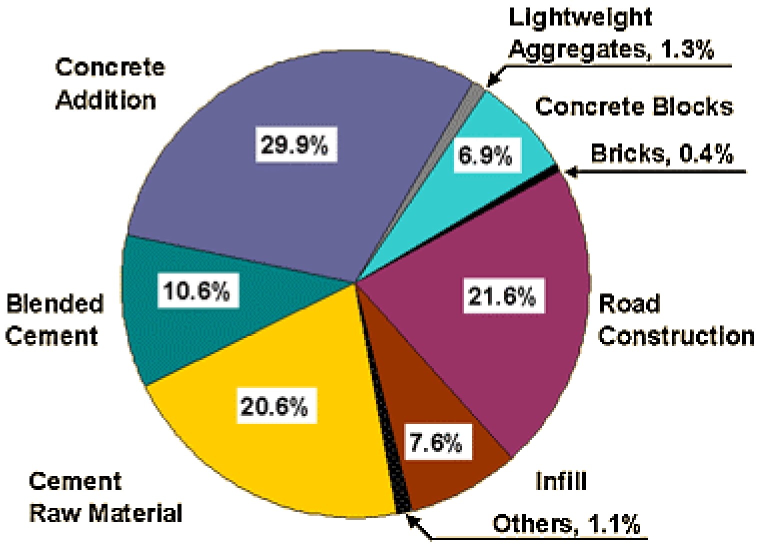


Figura 4 - Utilization of Fly Ash in the Construction Industry and Underground Mining in Europe (EU 15) in 1999
Total Utilization: 18.2 Million Tonnes

2.5.2 La situazione negli USA

Ogni anno si producono in USA circa 100 Mt di CCBs (vedi Tabella 8) di 41 Mt sono costituite da ceneri leggere di cui circa il 40% vengono riutilizzate (vedi le successiva Figura 5).
Fra i principali settori di riutilizzo citati, appaiono gli impieghi geotecnici, cui sono destinate circa il 21 % delle ceneri leggere riutilizzate. Tale percentuale supera il 45% in riferimento alle sole ceneri pesanti.

Tabella 8 - Produzione di rifiuti termoelettrici in USA (anno 1999, fonte ACAA – American Coal Ash Association)

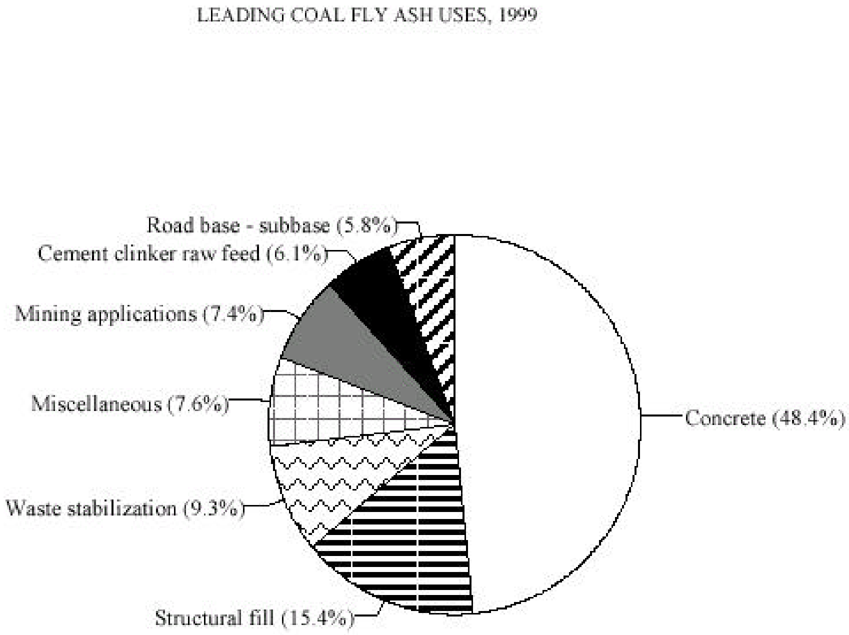
DRY COAL COMBUSTION PRODUCT (CCP) PRODUCTION AND USE, 1999

(Thousand metric tons)

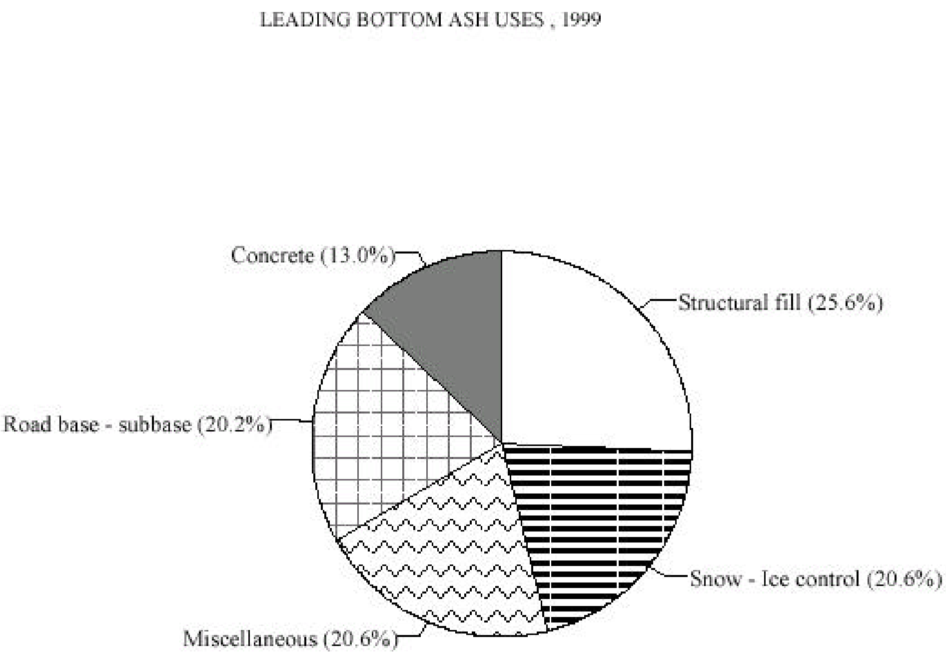
	Fly ash	Bottom ash	Boiler slag	FGD 1/ material	Total CCP's
Production:					
Disposed	22,900	6,000	40	13,800	42,700
Produced	41,400	9,100	800	17,600	68,900
Removed from disposal	180	180	--	--	360
Stored on-site	1,860	460	30	670	3,020
Use:					
Agriculture	10	40	--	70	120
Blasting grit-roofing granules	--	120	640	--	760
Cement clinker raw feed	1,060	130	--	--	1,190
Concrete-grout	8,540	430	--	260	9,230
Flowable fill	720	10	--	--	730
Mineral filler	140	50	10	--	200
Mining applications	920	50	10	210	1,190
Roadbase-subbase	990	620	--	20	1,630
Snow and ice control	--	500	10	--	510
Soil modification	70	20	10	--	100
Structural fills	2,390	400	30	500	3,320
Wallboard	--	--	--	1,910	1,910
Waste stabilization-solidification	1,750	60	--	10	1,820
Other	280	380	30	160	850
Total	16,900	2,810	740	3,140	23,600
Individual use percentage	40.70	30.70	93.00	17.90	NA
Cumulative use percentage	40.70	38.90	39.70	34.20	34.20

NA Not available. -- Zero.
1/ FGD, flue gas desulfurization.

Figura 5 - Principali settori di impiego delle ceneri di carbone negli USA



Source: American Coal Ash Association.



Source: American Coal Ash Association.

2.6. Prodotti e tecnologie di riutilizzo

2.6.1 Cementi e calcestruzzi

Le ceneri leggere possono essere utilizzate, in tale settore,:

- come materia prima per la produzione di clinker di Portland in sostituzione dell'argilla (rappresenta un impiego a ridotto valore economico ma privo di specifici requisiti)
- come aggiunta al clinker per la produzione di cementi di miscela (in accordo alle prescrizione della UNI ENV 197/1 già descritta)
- come materia prima per il confezionamento di calcestruzzi in aggiunta o parziale sostituzione del cemento (UNI ENV 206 e UNI EN 450).

In entrambe queste ultime applicazioni, le ceneri leggere di carbone agiscono principalmente come microfiller e come aggiunta pozzolanica.

L'elevata finezza e la forma sferoidale delle particelle di cenere leggera migliorano infatti molte proprietà del calcestruzzo fresco, quali la lavorabilità, la pompabilità e l'assenza di segregazione (bleeding).

Esse sono inoltre capaci di reagire chimicamente a temperatura ambiente con l'idrossido di calcio liberato dall'idratazione del cemento Portland, dando origine a silico-alluminati idrati di calcio, simili a quelli prodotti dal cemento stesso.

Tutti i calcestruzzi prodotti con solo cemento di Portland generano un eccesso di calce che rappresenta un componente di indebolimento per il calcestruzzo poiché è un materiale poroso, chimicamente vulnerabile agli acidi e all'anidride carbonica ed è solubile in acque solfatiche. L'adozione di un materiale pozzolanico come le ceneri, capace di reagire con la calce fissandola in prodotti di reazione stabili e ad elevata idraulicità, consente quindi di ottenere il molteplice risultato di migliorare la resistenza del calcestruzzo e di renderlo meno permeabile e più resistente agli attacchi chimici.

Le ceneri leggere utilizzate ad integrazione del cemento Portland possono quindi essere impiegate sia da parte del produttore di cemento, con l'ottenimento di cementi di miscela, sia da parte del produttore di calcestruzzo, che confeziona quest'ultimo adottando direttamente le ceneri come materia prima, al fianco di cemento, acqua ed aggregati.

Nel caso della sostituzione di parte del cemento con ceneri leggere, si nota un più lento sviluppo delle resistenze alle basse stagionature (3-10 gg) a causa della reazione ritardata con la calce, sebbene vengano raggiunte le medesime resistenze finali (28 gg). Tale aspetto può talvolta rappresentare un inconveniente (facilmente risolvibile dosando opportunamente i normali additivi sempre utilizzati per regolare la presa e l'indurimento dei calcestruzzi), ma costituisce spesso un vantaggio nel caso di getti massivi in virtù del ridotto gradiente termico che si viene a definire in essi ed il conseguente ridotto pericolo di fessurazioni e difetti.

2.6.2 Laterizi

L'utilizzo di percentuali di cenere leggere del 15-25% in peso nella formulazione dei laterizi in argilla cotta è una pratica industriale consolidata, sebbene economicamente non molto remunerativa. In essi la cenere leggera viene impiegata in sostituzione della sabbia o della chamotte (laterizi di scarto macinati) per contrastare il normale ritiro delle argille all'essiccazione ed alla cottura, dando stabilità dimensionale al prodotto finito (mattoni o blocchi estrusi o stampati).

Inoltre, in virtù del tenore di carbone incombusto in esse presenti, le ceneri contribuiscono in parte al fabbisogno energetico del ciclo produttivo.

2.6.3 Aggregati artificiali leggeri

Attraverso il trattamento di agglomerazione su piatto o tamburo rotante con la sola aggiunta di acqua (ca. 25% in peso) e la successiva sinterizzazione termica a 1200 °C, è possibile trasformare le ceneri in aggregati artificiali alleggeriti (grado di vuoto approx. 40%).
La sinterizzazione, che genera una fase liquida capace di saldare le particelle di cenere in una matrice vetrosa ad alta resistenza, può essere eseguita adottando forni a tamburo rotante o a griglia mobile.
Gli inerti artificiali ottenuti presentano una densità in mucchio di 850 kg/m^3 ed una resistenza a schiacciamento in mucchio di 80 kg/cm^2. Essi possono essere utilizzati in sostituzione degli aggregati naturali o dell'argilla espansa per la produzione di calcestruzzi, sia gettati in opera che sotto forma di manufatti prefabbricati, per applicazioni strutturali o con funzione di isolamento termico ed acustico.

3. Le ceneri nella realizzazione di rilevati e sottofondi stradali

3.1 Aspetti tecnici

Vengono di seguito riportate delle brevi schede descrittive delle modalità di utilizzo delle ceneri nei settori di impiego oggetto dello studio, richiamando le principali proprietà dei prodotti finali ottenibili. Per un ulteriore approfondimento degli aspetti tecnici descritti, si rimanda inoltre all'Allegato 5 al presente rapporto. In esso vengono riportate le schede tecnico informative elaborate dalla UKQAA (UK Quality Ash Association) in relazione alle applicazioni di seguito analizzate.

3.1.1 L'utilizzo di ceneri di carbone nella realizzazione di rilevati e riempimenti strutturali[4]

Con i termini di rilevati e riempimenti si intendono volumi di materiale terroso posti in opera e compattati al fine adattare il piano di posa stradale alle esigenze di progetto, modificandolo rispetto al livello naturale del terreno. I rilevati sopraelevano la superficie naturale, adattandola ad esempio alla realizzazione di una rampa di salita, mentre i riempimenti hanno il compito di colmare depressioni o fosse del terreno. Normalmente sono formati da un primo strato di materiale di pezzatura maggiore, con il compito di fornire una base stabile e con buona capacità drenante, cui viene sovrapposto uno strato di materiale più pregiato, ben distribuito granulometricamente e ben compattato.

Le ceneri leggere di carbone sono state largamente utilizzate con successo nei riempimenti strutturali o come materiale per rilevati in varie costruzioni stradali in Europa e all'estero (USA, Canada, Giappone). Opportunamente umidificata essa può infatti essere maneggiata facilmente e compattata fino ad esibire buone caratteristiche di coesione interna. Le prime esperienze di utilizzo risalgono agli anni '50 in Gran Bretagna.
La maggior parte della cenere volante usata per la costruzione di rilevati deriva da carboni antracitici e bituminosi (ceneri siliciche). Le ceneri da lignite o da carbone subbituminoso (cosiddette calciche, non oggetto del presente studio), in virtù della loro capacità autocementante, possono infatti indurire prematuramente allorché umidificate, determinando problemi di scarsa lavorabilità ed inabilità a raggiungere il grado richiesto di compattazione.
Studi condotti negli Stati Uniti dalla ACAA (American Coal Ash Association) hanno evidenziato come dal 1970 in almeno 14 stati americani sono state usate le ceneri volanti per costruire o riparare terrapieni e strade. La cenere volante è stata usata anche come un materiale da riempimento strutturale in prossimità delle spalle dei ponti ed in prossimità dei muri di sostegno. In nessuno Stato interessato è stata manifestata alcuna insoddisfazione in merito ai risultati ottenuti da tali applicazioni. Numerose di esse sono state monitorate durante e dopo la costruzione per valutarne le prestazioni per un periodo di tempo superiore a 3 anni. Il monitoraggio è consistito nel campionamento e la determinazione delle caratteristiche fisiche e tecniche delle ceneri, valutandone il comportamento nelle operazioni di posa in opera e di compattazione, prelevando da pozzi di monitoraggio e analizzando campioni di acqua di falda e prendendo periodicamente misure topografiche di ogni rilevato per valutarne gli assestamenti. Nessun caso applicativo ha mostrato cedimenti o problemi di impatto ambientale in relazione al periodo di indagine.

[4] Informazioni tratte da http://www.tfhrc.gov in base a valutazioni e studi condotti dall' US Department of Transportation - Federal Highway Administration

Quando usata in riempimenti strutturali o rilevati, la cenere volante offre diversi vantaggi rispetto ai terreni o inerti naturali. Il suo peso specifico relativamente basso, infatti, appesantisce in modo limitato il sottofondo, minimizzando gli eventuali cedimenti e le tensioni nel terreno. Inoltre le caratteristiche di resistenza al taglio, comparate con il limitato peso specifico, mettono in risalto tali vantaggi tecnici. La facilità di posa in opera e di compattazione, specialmente se la cenere viene fornita con un contenuto di umidità prossima a quella ottimale, permette di ridurre i costi di costruzione e di mano d'opera. Nelle aree in cui le ceneri sono disponibili in quantità massive viene inoltre ridotto sensibilmente il costo di approvvigionamento del materiale, rendendolo competitivo rispetto ai materiali sostitutivi estratti da cava.

- *Requisiti per la lavorazione del materiale*

La sola caratteristica soggetta a controllo durante la posa in opera è l'umidità. Il contenuto di umidità ottimale viene determinato prima dell'applicazione mediante prove Proctor standard.
La cenere stoccata nei silos dovrà quindi essere umidificata prima del caricamento e trasporto, prevenendo in tal modo anche ogni dispersione del materiale durante le precedenti fasi.
Nel caso di cenere estratta da bacini, se essa contiene un grado di umidità elevato, dovrà essere preliminarmente de-umidificata spandendola in prossimità del deposito e trasportata in cantiere dopo averne controllato il contenuto di acqua.

- *Caratteristiche tecniche*

Le principali proprietà tecniche di interesse per l'impiego delle ceneri leggere nei rilevati o come materiale di riempimento sono: il rapporto umidità/densità, la distribuzione granulometrica, la resistenza al taglio, le caratteristiche di consolidamento, quelle di portanza e la permeabilità.

Rapporto umidità/densità: La cenere volante compattata ha una densità relativamente bassa, con conseguente riduzione del carico applicato sugli strati sottostanti che sostengono il manufatto. Se le operazioni di compattazione vengono eseguite a perfetta regola d'arte e con un contenuto di umidità ottimale (generalmente dal 20 al 35 % in peso), si raggiungono densità, sul secco, maggiori di 1380 kg/cm^3 e fino a 1620 kg/cm^3.

Distribuzione granulometrica: La cenere volante è prevalentemente un materiale limoso, non plastico. Il 60 - 90 % delle particelle presenta un diametro inferiore di 75 µm (passante al setaccio n° 200). Come tale, la sua distribuzione granulometrica la colloca fra i materiali normalmente riconosciuti come terre suscettibili al gelo. La sua granulometria fine impone inoltre in ogni fase di manipolazione un contenuto di acqua sufficiente ad evitarne la polverosità. Dal momento che le terre a granulometria fine possono essere facilmente erose, una sufficiente umidità deve inoltre essere presente per garantire un sufficiente grado di compattazione.

Sforzo di taglio: Le prove di resistenza a taglio condotte su campioni di ceneri leggere appena compattate mostrano che le resistenze derivano maggiormente dall'attrito interno. Lo sforzo di taglio è funzione della densità e del contenuto di umidità del campione, con le massime prestazioni nella condizione di umidità ottimale determinata mediante la prova Proctor standard. L'angolo di attrito interno varia tra 26° e 42°, con valori medi tipici di 34°.

Caratteristiche di consolidamento: Un rilevato o riempimento strutturale dovrebbe possedere una bassa compressibilità per minimizzare i cedimenti stradali o cedimenti differenziati tra strutture e accessi adiacenti. Il consolidamento dei rilevati con ceneri si completa tipicamente durante la fase stessa di realizzazione del manufatto non creando rischi di successivi danni all'opera finita, a differenza di quanto accade soprattutto nel caso di impiego di terreni argillosi o limosi nei quali tali fenomeni di subsidenza possono protrarsi anche per lunghi periodi.

Capacità portante: I valori della prova CBR (California bearing ratio) per le ceneri leggere siliciche si attestano nel range da 10 a 16 %. Nel caso dei terreni naturali di riporto, il CBR varia nel range da 3 a 15 % per i materiali a grana fine (limi e argille), da 10 a 40 % per le sabbia ed i terreni sabbiosi e da 20 a 80 % per ghiaie e i terreni ghiaiosi.

Permeabilità: Dal momento che la cenere volante è costituita quasi interamente di particelle sferiche, queste possono essere facilmente addensate durante la compattazione, ottenendo bassi valori di permeabilità e minimizzando i fenomeni di percolazione di acqua attraverso il rilevato. La permeabilità di una cenere ben compattata varia nel range da 10^{-4} a 10^{-6} cm/s

- *Considerazioni di progetto*

Virtualmente ogni cenere leggera può essere usata per realizzare rilevati o quale materiale di riempimento strutturale, includendo la cenere stoccata ad umido nei bacini. Le principali considerazioni tecniche riferite alla progettazione di rilevati o riempimenti strutturali con impiego di ceneri leggere sono essenzialmente le stesse che vengono fatte quando è previsto l'impiego di terre naturali. Una particolare attenzione andrà tuttavia rivolta ai seguenti aspetti.

Drenaggio del sito: La cenere volante, a causa della predominanza della frazione limosa, trattiene al suo interno l'acqua, facendo sì che gli strati più bassi del rilevato possano divenire saturi, con conseguente perdita di resistenza a taglio. È perciò importante che la base di un riempimento in cenere volante non sia soggetta ad accumuli di acqua libera. Un modo efficace per prevenire risalite capillari o fenomeni di accumulo di acque percolazione nei terrapieni consiste nel posizionare uno strato drenante di materiale granulare alla base del manufatto ad una altezza di almeno 1.5 metri al di sopra del massimo livello storico di falda.

Stabilità del pendio: Per determinare l'inclinazione del pendio in fase di progettazione (rapporto tra la quota verticale e la distanza orizzontale), deve essere compiuta un'analisi della stabilità del pendio in una sezione trasversale rappresentativa. Il parametro principale che contribuisce alla stabilità è la resistenza al taglio del materiale che costituisce il rilevato. Per la stabilità a lungo termine dei terrapieni in cenere volante, è raccomandato un fattore di sicurezza (rapporto tra le forze resistenti e le sollecitazioni indotte lungo le superfici di potenziale frattura) di 1.5, considerando nei calcoli un valore di coesione del materiale pari a zero.

Controllo dell'erosione: La pendenza delle scarpate è importante anche in relazione alla potenziale erosione dei pendii in cenere volante compattata, influenzando la velocità di ruscellamento delle acque meteoriche e la esposizione ai venti. Una via per prevenire l'erosione è di coprire i pendi con strati di terreno naturale, ovvero stabilizzare la superficie dei pendii mediante aggiunta alle ceneri di modeste percentuali di cemento o calce.

Condizioni climatiche: Per ovviare ai potenziali inconvenienti del gelo, negli strati superficiali del rilevato possono essere aggiunte alle ceneri piccole quantità di calce o cemento.
Durante i periodi di pesanti o prolungate precipitazioni, il contenuto di acqua ottimale per la compattazione può essere ridotto per compensare gli effetti della precipitazione. La cenere

volante, diversamente dalla maggior parte delle terre, può essere posta in opera anche durante l'inverno, sebbene siano raccomandate temperature ambiente non sia inferiore a 4°C.

- *Procedure di costruzione*

Lavorazione e stoccaggio del materiale: La cenere volante pozzolanica è normalmente umidificata con acqua in impianto di centrale e trasportata in autocarri coperti e sigillati. Se nel sito di progetto viene realizzato uno stoccaggio provvisorio di cenere, la superficie dello stoccaggio deve essere tenuta abbastanza umidità per prevenire lo spolveramento. Lo stoccaggio dovrebbe essere posizionato in un area ben drenata e asciutta così che la cenere non venga interessata da accumuli d'acqua nel caso di eventuale pioggia.

Posa in opera e compattazione: Le attrezzature da cantiere necessarie per svolgere le operazioni di posa in opera e addensamento delle ceneri volanti per la realizzazione di un rilevato o per un riempimento strutturale comprendono: un bulldozer per la stesa del materiale, un compattatore vibrante o pneumatico, un'autobotte innaffiatrice per provvedere a distribuire l'acqua di compattazione (se necessaria) e per controllare o ridurre lo spolveramento, ed eventualmente una rasatrice per rifinire le superfici.
La cenere volante deve venire stesa in strati di spessore non superiore a 30 cm allo stato soffice. I migliori risultati sono stati ottenuti adottando compattatori vibranti a rullo di acciaio o a ruote pneumatiche. Se viene usato un rullo vibrante il primo passaggio dovrebbe esser fatto in condizioni statiche (senza alcuna vibrazione), seguito da passaggi con vibrazione veloce. In genere, sei passaggi di rullo risultano sufficienti per conseguire il grado di compattazione desiderato, pari al 90 - 95 % della densità Proctor standard misurata in laboratorio.
Le superfici delle ceneri volanti devono essere spianate e inclinate alla fine di ciascuno giorno lavorativo per provvedere al miglior drenaggio e prevenire ristagni di acqua o la formazione di ruscellamenti che potrebbero erodere pendi e produrre trasporto di sedimenti da parte delle acque superficiali. I pendii compattati in ceneri volanti devono inoltre essere protetti al più presto, dopo essere stati spianati. Il controllo dell'erosione sui pendii consiste nel porre da 150 a 600 mm di terreno di copertura. Un approccio alternativo consiste nel realizzare argini esterni per contenere l'eventuale trasporto di materiale per mezzo della pioggia.

Controllo di qualità: I programmi di controllo di qualità per rilevati o riempimenti strutturali a base di cenere volante sono simili ai programmi per progetti di lavori in terra convenzionali. Questi programmi tipicamente includono il controllo visivo dello spessore degli strati, del numero di passaggi del compattatore e del comportamento della cenere volante sotto il peso delle macchine compattatrici, oltre ad un completo esame di laboratorio ed un collaudo in sito per la verifica che le fasi di compattazione siano stata eseguite in accordo con quanto specificato dal progetto.

3.1.2 L'utilizzo di ceneri di carbone nelle miscele fluide per riempimenti[5]

Le miscele fluide per riempimenti sono miscele costituite principalmente da un aggregato fine (filler) ed acqua, ai quali vengono aggiunte piccole dosi di legante, caratterizzate dalla capacità di riempire vuoti di forma irregolare (trincee, cavità), autolivellarsi ed indurire in poche ore

[5] Informazioni tratte da http://www.tfhrc.gov in base a valutazioni e studi condotti dall' US Department of Transportation - Federal Highway Administration

raggiungendo resistenze comparabili a quelle del terreno circostante, senza alcuna operazione di stesa o compattazione del materiale.

La cenere volante può essere usata come materia prima per la produzione di miscele fluide autolivellanti e autocompattanti per riempimenti. Le miscele prevedono l'aggiunta di piccole percentuali di cemento Portland o calce, quali leganti e per attivare la reazione pozzolanica delle ceneri, ed eventualmente altri materiali da riempimento (nella maggior parte dei casi sabbia).
I valori di progetto delle resistenze a compressione dipendono dalla esigenza o meno di successive escavazioni dell'opera, nel qual caso le resistenze non dovrebbero eccedere 1 MPa. Sono tuttavia raggiungibili resistenze fino a 10 MPa e conseguenti elevate portanze, capaci di sostenere anche carichi derivanti da traffico veicolare.
Le miscele fluide contenenti ceneri volanti si possono distinguersi in due tipologie: ad alto contenuto (~95%) ed a basso contenuto (5-10%). Nelle prime le ceneri, oltre al ruolo di aggiunte pozzonaliche, sostituiscono integralmente gli inerti fini (sabbie) generalmente adottati.
Dal momento che le miscele fluide sono normalmente materiali a resistenza relativamente bassa, non vi è bisogno di misure severe per il controllo della qualità della cenere volante usata. Al fianco delle ceneri secche, possono anche essere utilizzate ceneri provenienti da bacini di stoccaggio ad umido. In ogni caso,non è previsto alcun processo speciale di lavorazione.
La particolare finezza e la forma sferoidale delle particelle di cenere migliorano la fluidità della miscela. La sua densità secca relativamente bassa contribuisce inoltre alla riduzione del peso del riempimento e le sue proprietà pozzolaniche determinano una ridotta richiesta di cemento rispetto a quanto normalmente necessario per raggiungere resistenze equivalenti nelle miscele tradizionali.

- *Proprietà tecniche*

Alle caratteristiche di sfericità delle particelle e di attività pozzolanica si legano, specie allorché le ceneri vengono utilizzate come componente principale della miscela fluida, le principali proprietà tecniche del manufatto finale. Fra queste la resistenza a compressione, la fluidità, la stabilità, la capacità portante, il modulo di reazione della fondazione, la pressione laterale, il tempo di presa, il bleeding e il ritiro, la densità e la permeabilità.

<u>Resistenza a compressione</u>: Lo sviluppo della resistenza a compressione è direttamente proporzionale al contenuto di cemento introdotto. Le miscele ad alto contenuto di cenere volante richiedono da 3 a 5 % in peso di cemento Portland per sviluppare a 28 giorni di stagionatura resistenze da 0,5 a 1 MPa. Le resistenze continuano tuttavia a crescere sensibilmente anche dopo i 28 giorni di stagionatura.

<u>Fluidità</u>: La fluidità influenza le modalità di posa in opera della miscela e la sua capacità di riempire i vuoti ed è quindi funzione del tipo di applicazione prevista. La fluidità dipende direttamente dal contenuto di acqua introdotto nella miscela. Essa può essere misurata usando un cono per la misura dello slump del calcestruzzo o un cono di flusso (flow cone test - ASTM C 939). I range di fluidità misurati con il cono per lo slump del calcestruzzo variano tra 150 a 200 mm. Non vengono usati additivi come agenti di riduzione dell’acqua di impasto. Nel caso di misure tramite *flow cone test*, valori tipici di fluidità corrispondono a tempi di deflusso di 30–40 secondi attraverso il cono di flusso standard.

<u>Stabilità</u>: Prove triassiali hanno indicato angoli di attrito interno tra 20° e 30°. I valori di coesione variano in proporzione alla resistenza a compressione: miscele con resistenze di 350 kPa hanno

esibito valori di coesione pari a 120 kPa, mentre miscele con resistenze di 700 kPa coesione pari a 200 kPa.

Capacità portante: La capacità portante delle miscele indurite varia proporzionalmente alla resistenza a compressione e all'angolo di attrito. Per esempio la capacità portante di miscele fluide con una resistenza di 700 kPa è risultata variabile nell'intervallo tra 80 e 150 t/m^2 per angoli di attrito tra 20 e 30°. Questo è approssimativamente da 2 a 4 volte la portanza dei migliori materiali ben compattati per terrapieni.
La prova CBR è anch'essa una misura della portanza in sito, utilizzata per verificare le qualità di una fondazione comparate con quelle di materiali standard in pietra frantumata. Prove CBR hanno esibito valori tra 40 e 90 %, con medie del 50%, su miscele fluide caratterizzate da una resistenza alla compressione di 700 kPa a 24 h dalla posa in opera.

Modulo di reazione della fondazione: Il modulo di reazione di una fondazione (k), usato per la progettazione di pavimentazioni, è normalmente compreso tra 8 e 50 N/cm^2 per la maggior parte delle terre e raggiunge 80 N/cm^2 per un buon materiale granulare da fondazione. Valori tipici di k misurati per miscele fluide per riempimenti sono di 800 N/cm^2 o più, comunque molto maggiori di quelli ottenibili con qualsiasi terra da riempimento.

Tempo di indurimento: Esso si riduce al crescere del contenuto di cemento nella miscela ed al ridursi del tenore di acqua utilizzato. Una tipica miscela fluida ad alto contenuto di cenere volante (col 5 % di cemento) indurisce sufficientemente per sostenere il peso di una persona media in 3 - 4 ore, in funzione della temperatura e dell'umidità. Entro 24 ore le macchine da cantiere possono operare sulla sua superficie senza provocare danni evidenti.

Bleeding e ritiro: Le miscele fluide con alto contenuto di cenere volante e con contenuto di acqua eccessivo tendono a rilasciare tale eccesso prima dell'inizio della presa. L'evaporazione dell'acqua trasudata spesso determina ritiri significativi (1%) tanto lateralmente quanto verticalmente. Una volta che il materiale ha superato il periodo di presa iniziale, non avviene più alcuna contrazione addizionale o cedimento a lungo termine sul manufatto.

Densità: Le miscele fluide ad alto contenuto di cenere volante sono di solito più leggere dei terreni naturali compattati. I valori tipici di densità possono variare tra 1450 e 1950 kg/m^3. Diminuzioni significative della densità (fino a 350 kg/m^3) si possono ottenere mediante l'impiego di additivi aeranti, allo scopo di determinare una riduzione del carico trasmesso dal manufatto sugli strati di appoggio.

Permeabilità: I valori di permeabilità delle miscele ad alto contenuto di cenere volante decrescono all'aumentare del contenuto di cemento e sono generalmente compresi tra 10^{-6} e 10^{-7} cm/sec.

- *Considerazioni di progetto*

Progetto della miscela: La miscela fluida per riempimenti con alto contenuto di cenere volante è proporzionata sulla base del percentuale di cemento Portland sul peso secco della cenere. Una miscela al 5 % di cemento Portland è abbastanza tipica. Il dosaggio di acqua da aggiungere alla miscela è dipendente dal grado di fluidità desiderato. Se la cenere volante viene fornita con un prestabilito contenuto d'acqua, bisogna tenerne conto nel calcolo della percentuale aggiunta. Nel caso delle miscele fluide a basso contenuto di cenere volante, la presenza di un ulteriore ingrediente, generalmente sabbia, consente una più vasta possibilità di progettazione.

Le miscele fluide vengono progettate per sviluppare una resistenza a compressione funzione del tipo di applicazione. Nel caso del riempimento di una trincea, ad esempio, valori di progetto si aggirano tra 700 kPa e 1000 kPa. Il tenore di cemento viene dosato mediante prove preliminari di laboratorio condotte su campioni cilindrici (di solito D 75 mm, H 150 mm) fatti stagionare in un contenitore sigillato a temperatura costante per 7, 28 e 90 giorni.

- *Procedure di costruzione*

Stoccaggio e posa in opera del materiale: Vengono solitamente adottate le medesime attrezzature utilizzate per il confezionamento delle miscele in calcestruzzo, di impianto o di cantiere. La cenere può essere immagazzinata allo stato secco, in silos, o allo stato umido. Se la cenere volante è stoccata in condizioni secche, l'area di stoccaggio dovrà essere provvista di umidificatori per prevenire qualsiasi dispersione di polveri nell'ambiente.
La miscela fluida può essere posta in opera per mezzo di pompe, nastri trasportatori, condotte o in altro qualsiasi modo impiegato per il calcestruzzo. Il materiale non richiede compattazione o vibrazione durante o dopo la posa in opera.
Nel caso in cui siano presenti muri di contenimento, è raccomandata la posa in opera in strati successivi per limitare la spinta laterale esercitata su di essi dal materiale fluido.
Nel caso del riempimento di trincee in presenza di tubi, è bene che essi, specie se di peso ridotto, vengano preventivamente assicurati sul fondo della trincea mediante ancoraggi o zavorre per prevenire il galleggiamento durante il getto della miscela che tende ad occupare gli spazi sottostanti.
La miscela fluida può essere posta in opera anche in presenza di acqua fluente o accumulatasi nello scavo. La miscela sposterà l'acqua, eliminando così l'esigenza di pomparla prima del getto.
Normalmente non vi sono particolari raccomandazioni per la stagionatura di queste miscele, benché durante i periodi di tempo caldo, può essere consigliabile coprire le superfici esposte per minimizzare l'evaporazione ed il conseguente sviluppo di fenomeni di ritiro e fessurazione.

3.1.3 Utilizzo delle ceneri di carbone nella realizzazione di fondazioni stabilizzate[6]

Nelle costruzioni stradali, il termine base o fondazione stabilizzata fa riferimento allo strato di pavimentazione intermedio fra manto superficiale, a diretto contatto con i mezzi mobili, ed il suolo sottostante, e ad esso è demandato il compito di trasmettere e distribuire il carico veicolare, specie nelle pavimentazioni flessibili.

La cenere volante può essere proficuamente utilizzata come componente di miscele stabilizzate per strati di base e di fondazione. In tal caso, la cenere volante silicica viene utilizzata in miscela con un legante (calce, cemento Portland o loppa d'altoforno), aggregati ed acqua. La quantità di cenere normalmente usata varia dal 10 al 30 % sul peso della miscela secca, in funzione della dimensione massima richiesta per gli aggregati.
L'uso della cenere volante nelle miscele stabilizzate per strati di base e di fondazione risale al 1950, quando fu brevettato negli USA un prodotto denominato Poz-o-Pac, costituito da una miscela di cemento, cenere volante ed aggregati.

[6] Informazioni tratte da http://www.tfhrc.gov in base a valutazioni e studi condotti dall' US Department of Transportation - Federal Highway Administration

Miscele stabilizzate a base pozzolanica sono state spesso utilizzate per strutture stradali destinate ad alto traffico (autostrade), oltre che per strade residenziali e locali. Le loro prestazioni sono legate alle resistenza sviluppate dalla reazione pozzolanica tra la cenere volante ed il legante aggiunto (calce o cemento), in modo analogo a quanto avviene nei calcestruzzi. Tuttavia, contrariamente al calcestruzzo, i prodotti stabilizzati sono posti in opera per mezzo di una consistente compattazione condotta nella condizione di umidità ottimale.

- *Requisiti di lavorazione del materiale*

Il principale parametro di controllo, durante le operazioni di lavorazione, è ancora il contenuto di umidità. Se viene utilizzato un impianto di betonaggio, è preferibile alimentare la cenere volante allo stato asciutto da un opportuno silo di stoccaggio. Se è altresì prevista la miscelazione dei materiali in cantiere, la cenere può anche essere approvvigionata con un contenuto di umidità del 10 – 15 %, sufficiente per evitare dispersioni di polvere nel cantiere e miscelata con gli altri componenti, previa successiva aggiunta di acqua, fino al raggiungimento del contenuto ottimale.
I leganti sono aggiunti quasi sempre in polvere. Gli aggregati sono introdotti nella miscela in una condizione di superficie satura. Il contenuto del umidità degli aggregati deve essere comunque controllato prima delle operazioni di miscelazione per assicurare che non vi sia stata variazione di umidità durante il periodo di stoccaggio.

- *Caratteristiche tecniche*

Le principali caratteristiche delle ceneri leggere significative per il loro impiego nelle miscele stabilizzate per basamenti e fondazioni sono: il contenuto dell'umidità, l'attività pozzolanica e la finezza.
Ad esse si legano le caratteristiche prestazionali del prodotto finale: la resistenza a compressione e a flessione, il modulo di elasticità, la capacità portante, il comportamento a fatica, la resistenza al gelo-disgelo e la permeabilità.

<u>Resistenza a compressione</u>: La misura della resistenza a compressione delle miscele stabilizzate è normalmente eseguita su provini Proctor del diametro di 10.2 cm e di altezza 11.7 cm, addensati con un contenuto di umidità ottimale. Entro certi limiti, la migliore qualità del materiale è fissata dalla più alta resistenza. Per le miscele stabilizzate con cemento alcune raccomandazioni richiedono una resistenza minima a compressione, dopo 7 giorni di stagionatura a 23°C, di 3 MPa. Nei casi in cui sia previsto l'uso di calce come legante, la norma ASTM C 593 impone una resistenza a compressione minima, dopo 7 giorni di maturazione a 38°C, di 2,76 MPa. Lo sviluppo delle resistenze a lungo termine può essere da due a tre volte superiore.
L'effettivo sviluppo della resistenza in campo dipendente, oltre che dal tempo di maturazione, anche dalla temperatura ambiente. All'aumentare della temperatura si registra un incremento della velocità di maturazione. A 4°C o meno, la reazione pozzolanica cessa virtualmente e la miscela non incrementa la sua resistenza. Comunque, una volta che la temperatura supera i 4 °C, la reazione pozzolanica riprende, accrescendo la resistenza della miscela. In questo modo le miscele stabilizzate con ceneri continuano a maturare lentamente per molti anni.

<u>Resistenza a flessione</u>: Poiché il materiale stabilizzato indurito forma uno strato di pavimentazione semi-rigido, la resistenza a flessione della miscela può essere un buon indicatore della sua resistenza effettiva in esercizio. Benché la resistenza a flessione possa essere determinata con una prova diretta, è consuetudine valutare tale parametro come una frazione della resistenza a

compressione. È considerato abbastanza accurato come valore di resistenza a flessione delle miscele stabilizzate un valore medio del 20 % della resistenza a compressione non confinata.

Modulo di elasticità: Il modulo di elasticità è una misura della rigidezza del materiale. Per materiali semi-rigidi come le miscele stabilizzate, il rapporto tra sforzo e deformazione non è lineare, perciò il modulo di elasticità non è un valore costante ma aumenta all'aumentare della resistenza a compressione del materiale. Nei calcoli previsti per la progettazione di pavimentazioni è consigliabile far riferimento al modulo di elasticità ricavato dalla prova di resistenza a flessione, invece della resistenza a compressione. Per molte miscele il modulo di elasticità varia da 10×10^6 kPa a 17×10^6 kPa.

Portanza: La prova CBR (California Bearing Ratio) è spesso usata per misurare la capacità portante dei materiali usati negli strati di fondazione per strade e pavimentazioni. In virtù dell'ottimo grado di addensamento ottenibile dalle operazioni di compattazione delle miscele stabilizzate con ceneri, non è insolito riscontrare valori elevati dell'indice CBR, anche superiori al 100 %.

Durabilità al gelo-disgelo: La prova di durabilità dei materiali stabilizzati viene eseguita applicando procedure di prova prestabilite. Per leganti a base di cemento, ad esempio, si può fare riferimento a quanto specificato nella norma ASTM D560 che prevede un valore massimo del 14 % di perdita in peso dopo 12 cicli di gelo-disgelo. Il requisito minimo di resistenza del manufatto prima del primo ciclo di gelo, in modo da garantire una sufficiente durabilità, è dipendente dalla severità dei cicli di gelo-disgelo. L'American Coal Ash Association (ACAA) raccomanda le resistenze minime a compressione di 7, 5 e 4 MPa, rispettivamente, per condizioni di gelo-disgelo severe, moderate e lievi.

Permeabilità: La permeabilità dipende principalmente dalla granulometria dell'aggregato presente nei materiale stabilizzato. Nelle miscele con ceneri essa è molto bassa in confronto a quella che si riscontra nelle fondazioni o basi in pietra frantumata e si avvicina a quella tipica degli strati di base in asfalto. Nella maggior parte dei casi, la permeabilità decresce all'aumentare della resistenza a compressione. I valori iniziali della permeabilità per materiali di base stabilizzati con ceneri possono variare tra 10^{-5} e 10^{-6} cm/s; col procedere della reazione pozzolanica, i materiali possono raggiungere valori di permeabilità tra 10^{-6} e 10^{-7} cm/s.

- *Considerazioni di progetto*

Progetto della miscela: Negli strati di base e di fondazione possono essere utilizzati aggregati con varie distribuzioni granulometriche. Dopo aver determinato la distribuzione granulometrica dell'aggregato da impiegare, la prima operazione da compiere è quella di ricercare la percentuale ottimale di fini, costituiti in tal caso dalle ceneri. L'operazione viene mediante prove di compattazione col metodo Proctor standard condotte su provini confezionati a partire da miscele in cui, assegnato un valore di tentativo dell'umidità, viene aumentato progressivamente il tenore di ceneri leggere. La densità raggiunta in rapporto al contenuto di materiale fine viene rappresentata su grafico cartesiano per riscontrarne le condizioni di massima densità ed individuando da questo la percentuale ottimale di fini in relazione all'aggregato utilizzato. (Per ovviare alle imperfette condizioni di compattazione in campo, il tenore di fini precedentemente valutato in laboratorio viene in genere aumentato di un paio di punti percentuali nelle miscele finali di progetto) Successivamente viene ottimizzato il contenuto d'acqua ripetendo le medesime prove Proctor, in cui, stavolta, viene mantenuto costante il tenore di fini e variato il tenore di umidità.

Determinati fini ed umidità ottimali, viene infine valutata la percentuale di legante necessaria a garantire le caratteristiche di resistenza e durabilità richieste dal progetto. Ciò viene condotto eseguendo misure di resistenza su provini confezionati in base a differenti miscele di tentativo, in accordo con le procedure riportate, ad esempio, nella norma ASTM C593.
Il quantitativo tipico di legante previsto per questo tipo di prodotto è risultato essere variabile, in rapporto con la quantità di cenere utilizzata, da 1:3 a 1:5 usando il cemento Portland.
La percentuale di cenere + legante determina la quantità di matrice cementante disponibile per riempire i spazi vuoti tra le particelle di aggregato. Per ottenere resistenze soddisfacenti, normalmente, tale somma varia tra il 15 ed il 30 % rispetto al peso secco della miscela totale, benché aggregati caratterizzati da una granulometria non molto ben distribuita richiedano una maggior quantità di fini. Per assicurare un adeguato fattore di sicurezza in cantiere, si adottano in genere tenori di legante maggiorati dello 0,5 % rispetto a quelli determinati in base alle prove di laboratorio.

- *Procedure di costruzione*

<u>Stoccaggio del materiale</u>: La cenere leggera usata nelle miscele stabilizzate pozzolaniche può esser impiegata allo stato secco, nel qual caso essa viene stoccata in silos, ovvero allo stato umido ed allora può essere accumulata su piazzali in aree adiacenti il cantiere. Se è previsto un prolungato periodo di stoccaggio, è necessario prevedere la periodica umidificazione dei cumuli per prevenire la dispersione di polvere in atmosfera.

<u>Miscelazione, spandimento e compattazione del materiale</u>: La miscelazione delle materie prime può essere eseguita in un apposito impianto di betonaggio o direttamente sul sito interessato all'opera. È comunque preferibile che avvenga in impianto, potendosi in tal caso meglio garantire il dosaggio dei componenti e la loro omogeneizzazione. Mediante la miscelazione in sito è comunque possibile ottenere risultati di ottima qualità. In tal caso, i vari componenti della miscela vengono stesi sulla carreggiata e successivamente omogeneizzati mediante idonee macchine da cantiere capaci di operare la miscelazione per una profondità di 30 – 45 cm.
Per la distribuzione dei materiali sull'area di lavoro vengono utilizzati i medesimi veicoli ribaltabili coperti usati per il trasporto delle materie prime o del materiale premiscelato in impianto. Una volta versato, il materiale viene successivamente distribuito mediante un bulldozer, ovvero utilizzando una macchina rasatrice.
Nelle operazioni di miscelazione sul campo, la cenere volante dovrebbe essere posta per prima sulla carreggiata, seguita dal legante (allo stato secco se costituito da cemento, spesso in forma di slurry nel caso della calce) ed infine ricoperta dagli aggregati previsti per la miscela. In tal caso, la cenere volante viene utilizzata pre-umidificata per minimizzare le dispersioni di polvere. L'acqua viene aggiunta secondo le necessità attraverso autobotti munite di opportuni spruzzatori.
Le macchine per la compattazione sono le stesse indipendentemente dal metodo di lavorazione della miscela (miscelazione in impianto o in cantiere) e costituite in genere da un compattatore vibrante a rullo di acciaio o a ruote pneumatiche.
La miscela stabilizzata pozzolanica viene compattato in strati successivi, ciascuno di spessore compreso tra 10 e 20 cm (circa 15-25 cm allo stato sciolto). La superficie di ogni strato dovrebbe venire leggermente scarificata prima di stendere lo strato successivo.

Stagionatura: Dopo la stesa e la compattazione del materiale stabilizzato, la superficie dello strato finito deve essere protetta per evitarne l'essiccazione e permettere lo sviluppo delle reazioni idrauliche. Se è prevista una pavimentazione in conglomerato bituminoso potrà essere applicato sull'ultimo strato una pellicola di emulsione bituminosa, entro 24 ore dalla fine della compattazione. Le prestazioni della pavimentazione sono dipendenti dallo sviluppo delle resistenze in sito funzione delle modalità di posa in opera, del grado di compattazione e della stagionatura. È necessario sempre verificare il grado di maturazione raggiunto rispetto a quanto previsto in sede di progettazione prima di porre in esercizio la pavimentazione. E' in ogni caso sconsigliato far veicolare mezzi di alcun genere se non è stata raggiunta una resistenza di almeno 2,5 MPa. Normalmente, la realizzazione di una pavimentazione in asfalto o in conglomerato cementizio sul materiale stabilizzato è raccomandata dopo 7 giorni dalla posa in opera dello stesso.

Condizioni climatiche per la costruzione: Questi materiali possono sopportare gli stress dovuti all'azione del gelo-disgelo ma solo dopo che si sono sviluppate le resistenze attese. È pertanto necessario che la posa in opera non avvenga in condizioni climatiche sfavorevoli. Normalmente, per garantire un minimo sviluppo delle resistenze è necessario che la temperatura ambiente non sia inferiore a 5°C.

Controllo delle fessurazioni: Gli strati di fondazione e base di pavimentazioni realizzate con materiali stabilizzati con pozzolane possono essere soggetti, come in genere ogni manufatto cementizio di dimensioni massive, a fessurazioni per effetto dei fenomeni di ritiro. Alcune fessure possono riflettersi sulle pavimentazioni in asfalto; mentre sono meno probabili nelle pavimentazioni in calcestruzzo. Se le fessure superficiali appaiono prima della posa in opera dello strato di usura, possono essere sigillate per prevenire l'intrusione di acqua.

3.1.4. Evoluzione normativa in corso

L'impiego delle ceneri di carbone per impieghi stradali è attualmente oggetto di studio tecnico a livello comunitario da parte del CEN/TC 227 "Road materials" WG 4 " Hydraulic bound mixtures and unbound mixtures".

In particolare, sono in fase di redazione due norme tecniche, attualmente allo stadio *CEN-inquiry*, il cui esito è atteso entro la fine dell'anno. Il titolo assegnato ai due pre-standard è:

- **prEN (TC 227 WI 190)** "Unbound and hydraulically bound mixtures - Part 3: Fly ash bound mixtures - Definitions, composition, classification"
- **prEN (TC 227 WI 191)** "Unbound and hydraulically bound mixtures - Part 4: Fly ash for hydraulically bound mixtures - Definitions, composition, classification"

Essi vengono riportati (versione Agosto 2000) negli Allegati 4 e 5 al presente rapporto.

I requisiti di controllo qualità richiesti per le ceneri leggere siliciche, così come indicati dalla pre norma **prEN (TC 227 WI 191)** sono riportati nella successiva Tabella 9.

Il pre-standard **prEN (TC 227 WI 190)** specifica altresì i costituenti, la composizione e la classificazione di laboratorio delle *Miscele legate a base di Ceneri Leggere* (denominate FABS - Fly Ash Bound Mixtures) per impieghi stradali (strati di base, sottofondazioni, ecc.). Rimandando all'Allegato 2 per ulteriori approfondimenti, nella successiva Tabella 10 si richiamano gli esempi di composizione delle miscele riportate a titolo indicativo nell'*Annex C* alla medesima proposta di norma europea.

Tabella 9 - Requisiti di controllo qualità per le ceneri siliciche previsti in base alla pre-norma **prEN (TC 227 WI 191)**

Caratteristica		Requisito di accettazione	Procedura di prova
Finezza %	**passante a 90 mm**	≥ 70	EN 451-2
	passante a 45 mm	≥ 40	
Perdita al fuoco (LOI) (%)		≤ 10.0	EN 196-2
Solfati (SO_3) (%)		≤ 4.0	EN 196-2
Calce libera (CaO_{lib})		≤ 1.0	EN 451-1
Stabilità dimensionale (mm) (pasta normale, 50 cen : 50 cem)		≤ 10	EN 196-3
Attività pozzolanica		Se richiesta, su base nazionale	EN 450, EN 196-1

Tabella 10 - *Annex C (informative)* alla proposta di norma Europea prEN (TC 227 WI 190):

Examples of fly ash bound mixtures (FABM) for road and airfield construction using siliceous fly ash

Ref	Type	Examples	Typical proportions as a percentage of dry mass %						Typical water content %	Age[a] of performance testing days
			Siliceous Fly Ash	Lime[b]	Cement	Sand	Coarse aggregate	Other Material		
1	FABM1	Fly Ash / Lime	93 to 97	3 to 7	—	—	—	—	15 to 25	90
2		Fly Ash / Lime / Gypsum	91	4	—	—	—	5 % gypsum	15 to 25	90
3		Fly Ash / Cement	90 to 95	—	5 to 10	—	—	—	15 to 25	28
4	FABM2	Fly Ash / Lime / Granular Material	4 to 13	1 to 3	—	30 to 40	50 to 55	—	6 to 8	90
5		Fly Ash / Cement / Granular Material	3 to 6	—	1 to 3	40 to 45	50 to 55	—	6 to 8	28
6		Fly Ash / GBS[c] / Granular Material	5 to 7	0 to 2	—	30 to 40	50 to 55	5to7 %GBS[c]	6 to 8	90
7	FABM3	Fly Ash / Lime / Sand	9 to 12	2 to 4	—	84 to 89	—	—	~10	90
8		Fly Ash / Cement / Sand	6 to 8	—	2 to 4	88 to 92	—	—	~10	28

[a] Earlier age testing is permissible subject to data and experience.

[b] Lime means CaO or $Ca(OH)_2$, and may be supplied preblended with dry fly ash.

[c] Granulated blast furnace slag.

3.2 Aspetti ambientali

3.2.1 Considerazioni generali sui potenziali impatti ambientali legati all'impiego di materiali non convenzionali in applicazioni geotecniche

Sebbene non vi sia un sistema codificato di procedure e criteri per stabilire la compatibilità ambientale dell'uso di un rifiuto o un sottoprodotto in un'applicazione geotecnica, si possono individuare alcuni principi base per valutare i potenziali impatti sull'ambiente associati a questo tipo di applicazioni. Fra questi: 1) identificare i potenziali pericoli associati all'uso del materiale; 2) identificare i potenziali bersagli ad essi relativi (aria, acqua, suolo); 3) identificare l'entità dei potenziali impatti.

- *Identificazione dei potenziali pericoli associati all'uso del materiale*:

Il rifiuto di cui si intende valutare le potenzialità di riutilizzo può contenere metalli in tracce o elementi organici in tracce in concentrazioni maggiori o in condizioni di maggiore mobilità rispetto a quelle che riscontrate nei materiali convenzionali. Ovvero esso può contenere sostanze alcaline (ad es. calce libera) o alte concentrazioni di sali solubili o particelle molto fini suscettibili di dispersione atmosferica ed inalazioni. Il rifiuto può ancora contenere materiali volatili, organici o inorganici, suscettibili di rilasci in ambienti ad alta temperatura (ad esempio a seguito della posa in opera a caldo di manti bituminosi).
Nella successiva Tabella 11 vengono riassunte le principali proprietà di un generico rifiuto rilevanti ai fini ambientali.

Tabella 11 - Proprietà chimico-fisiche di un generico rifiuto rilevanti dal punto di vista ambientale

Parametro	*Proprietà potenzialmente pericolosa*
Metalli in tracce lisciviabili o solubili	Presenza di metalli rilasciabili quali As, Cd, Cu, Cr, Hg, Pb, Zn, ecc., che possono inquinare la qualità delle acque superficiali e di falda
Elementi organici in tracce lisciviabili o solubili	Presenza di tracce di sostanze organiche estraibili quali benzene, fenoli, cloruro di vinile, ecc., che possono inquinare le acque superficiali e di falda. Presenza di composti fortemente alcalini o acidi che possono alterare i naturali valori di pH delle acque superficiali e di falda.
Sali solubili	Presenza di sali solubili e ad alta mobilità che possono degradare la qualità delle acque e di ecosistemi acquatici sensibili.
Polveri totali ed inalabili	Presenza di particolato fine che può essere inalato o trasportato dai venti.
Metalli in tracce presenti nelle polveri totali ed inalabili	Presenza di metalli pesanti nelle polveri che possono essere inalate o depositate in siti secondari.
Sostanze organiche in tracce presenti nelle polveri totali ed inalabili	Presenza di sostanze organiche in tracce nelle polveri che possono essere inalate o depositate in siti secondari.
Metalli volatili	Presenza di metalli volatili, come As, Hg, Cd, Pb e Zn, che possono

	essere rilasciati ad alte temperature (soprattutto in relazione all'esposizione del personale di cantiere)
Sostanze organiche volatili	Presenza di sostanze organiche, quali gli idrocarburi clorurati, che possono essere rilasciati ad alte temperature (soprattutto in relazione all'esposizione del personale di cantiere)

- *Identificazione dei potenziali bersagli*:

La costruzione, l'esercizio e la gestione a fine vita di rilevati, riempimenti e strutture stradali comporta una serie di operazioni sui materiali componenti utilizzati quali: stoccaggio, vagliatura, macinazione, umidificazione, miscelazione, trasporto, essiccazione, carico e scarico, stesa, compattazione, esercizio nelle diverse condizioni di carico ed ambientali, demolizione, riciclaggio. Valutare ciascuna di queste fasi operative è essenziale per identificare di volta in volta i potenziali bersagli di eventuali fenomeni di rilascio di polveri, emissione di elementi volatili, lisciviazione di elementi in tracce, siano essi l'aria, le acque superficiali o di falda, il suolo, l'ambiente di lavoro. Ed è altrettanto fondamentale per valutare di volta in volta i controlli e le disposizioni necessarie a evitare o mitigare i potenziali impatti.

Identificare l'entità degli impatti:

Le tecniche di valutazione dell'entità degli impatti dipendono in gran parte dal tipo di valutazione che si intende condurre (valutazione d impatto ambientale, analisi di rischio per la salute, analisi di rischio ecologico), adottando di volta in volta opportuni modelli comportamentali per la sorgente emissiva, l'atmosfera, le acque superficiali, il suolo, le acque di falda. Il più delle volte, non esistono criteri e metodi standardizzati o estendibili a tutti i casi, ed è spesso necessario fare ricorso a verifiche dimostrative in campo a supporto dei risultati conseguiti.

3.2.2 La caratterizzazione ambientale dei rifiuti e l'attività normativa in corso

Affinché un rifiuto possa essere riutilizzato esso deve essere capace di sostituire materiali già in uso (leganti, sabbia, aggregati, filler, ecc.), rispettando precisi requisiti tecnici tipici di ciascuna destinazione d'uso, quali la granulometria, le resistenze meccaniche o la reattività rispetto ad altri componenti. Inoltre, i suoi costi devono essere minori di quelli del materiale che sostituisce ed i suoi quantitativi e disponibilità geografiche devono risultare almeno equivalenti.

Tuttavia, perché un rifiuto possa essere riutilizzato esso deve soprattutto risultare ambientalmente sicuro. La qualificazione ambientale di un rifiuto implica la considerazione delle sue proprietà intrinseche (caratteristiche fisico-chimiche), ma anche del suo comportamento a breve e lungo termine nelle condizioni e nello specifico scenario ambientale proprio della sua destinazione d'uso finale. Ciò riguarda la possibilità, in tali condizioni, di lisciviare elementi potenzialmente inquinanti, le caratteristiche e le potenziali interazioni con l'ambiente circostante dei prodotti di lisciviazione e, infine, le capacità ricettive dell'ambiente di destinazione.

A seguito della qualificazione ambientale del rifiuto in base ad analisi e metodi di prova del suo comportamento e riconosciuta la sua compatibilità ambientale in relazione alla specifica destinazione di riutilizzo considerata, è quindi possibile limitare i successivi controlli a procedure semplificate di conformità.

Questi principi operativi di determinazione della compatibilità ambientale di un rifiuto hanno carattere generale e sono i medesimi suggeriti dalla Direttiva Europea 99/31/CE sulle Discariche di Rifiuti in riferimento alla qualificazione ed al successivo controllo dei rifiuti da destinare alle diverse tipologie di discariche. In Allegato II § 3 della Direttiva si raccomandano infatti tre distinti livelli di caratterizzazione e verifica, di seguito riportati:

Livello 1: Caratterizzazione di base. Consiste nel determinare approfonditamente, in base ad analisi standardizzate e a metodi di prova del comportamento, il comportamento a breve e a lungo termine del colaticcio e/o le caratteristiche dei rifiuti.

Livello 2: Verifiche di conformità. Consistono in prove, eseguite a intervalli regolari con l'ausilio di analisi normalizzate e metodi di prova del comportamento più semplici, intesi a determinare se un tipo di rifiuti sia conforme a condizioni inerenti all'autorizzazione e/o a criteri di riferimento specifici. Le prove sono incentrate su variabili e comportamenti fondamentali individuati mediante la caratterizzazione di base.

Livello 3: Verifica in loco. Viene eseguita con metodi di controllo rapido per confermare che i rifiuti in questione sono gli stessi che sono stati sottoposti alle verifiche di conformità e che sono descritti nei documenti di accompagnamento. Può consistere nella semplice ispezione visiva di una partita di rifiuti.

L'attività di qualificazione precedentemente delineata, sia in riferimento al riutilizzo che allo smaltimento dei rifiuti, è ancora attualmente in fase di studio e definizione a livello europeo da parte del CEN/TC 292 "Characterisation of wastes".

Nella successiva Tabella 12 viene riportata una sintesi dei principali Standard in fase di elaborazione.

Alla base della nuova concezione di compatibilità ambientale vi è quindi la contemporanea considerazione della "sorgente" e dell' "ambiente ricettore". La compatibilità ambientale di un rifiuto può, di conseguenza, essere definita come la situazione in cui il flusso di inquinanti derivanti dal rifiuto, collocato in un determinato contesto idrogeologico e bio-fisico-chimico, è compatibile con le capacità di attenuazione del ricettore ambientale. La valutazione della compatibilità ambientale rechiede pertanto la considerazione di tre distinti termini:

- il comportamento della sorgente, ovvero l'emissione di flussi contenenti sostanze inquinanti da parte del rifiuto, funzione delle sue caratteristiche intrinseche e delle sue condizioni *in situ* (portata dei flussi liscivianti e relative caratteristiche, fra cui ad es. il pH, permeabilità del mezzo, condizioni di legame idraulico con altre componenti, ecc.);
- le modalità di trasporto e di interazione dei precedenti flussi con i mezzi attraversati;
- la capacità di ricezione ed attenuazione dei flussi inquinanti da parte dell'ambiente ricettore.

Tabella 12 - Metodi di caratterizzazione contemplati negli standard sviluppati dal CEN / TC 292 "Characterization of waste" rilevanti per la qualificazione ambientale delle ceneri di carbone negli impieghi geotecnici

Proprietà generali dei rifiuti:		
Proprietà / parametro	*Descrizione del test*	*Standard CEN/TC292*
Capacità di neutralizzazione acido/base (ANC/BNC)	Stabilire la capacità del rifiuto di agire come tampone chimico; elevate capacità ANC/BNC possono influenzare il pH di eventuali percolati	WI 2920032
Analisi dei rifiuti tal quali:		
Proprietà / parametro	*Descrizione del test*	*Standard CEN/TC292*
Contenuto di elementi dopo digestione acida	Determinazione del contenuto di una serie di elementi inorganici potenzialmente inquinanti	prEN13656, prEN 13657, ENV12506, prEN13370 (non tutti i parametri sono contemplati)
Test di eluizione:		
Test	*Descrizione del test*	*Standard CEN/TC292*
Test di percolazione con flusso ascendente	Determinazione del comportamento all'eluizione a breve e lungo termine, in condizioni di saturazione	WI 292034
Test di percolazione con flusso discendente	Determinazione del comportamento all'eluizione a breve e lungo termine, in condizioni di normale percolazione.	WI 292035
Test di percolazione a pH stabiliti	Determinazione del comportamento all'eluizione in condizioni di pH alterato (provocato dall'interazione dell'eluente con altri componenti del sistema)	WI 292032 e WI 292033
Test di disponibilità	Determinazione della disponibilità potenziale di costituenti inorganici in condizioni ottimizzate (ma non estreme), per stabilire il quantitativo totale di costituenti estraibili a tempi estremamente lunghi in condizioni variabili; il metodo può essere utilizzato come strumento preliminare per stabilire un programma analitico per altri test di eluizione	WI 292010
Test di simulazione di diffusione di componenti inorganici	Determinazione del comportamento a lungo termine di materiali monolitici (con determinate caratteristiche geometriche e di durabilità), controllato da meccanismi di diffusione.	WI ?

Analisi degli eluati da rifiuti:		
Proprietà / parametro	*Descrizione del test*	*Standard CEN/TC292*
pH	Determinazione dell'acidità dell'eluato; il pH dell'eluato può influenzare in modo determinante il comportamento di tutto il sistema alla lisciviazione	ENV 12506
Conducibilità elettrica	Determinazione del rilascio globale di sali da parte del rifiuto e della sua capacità di scambiare ioni con l'ambiente circostante	prEN 13370
Costituenti inorganici	Determinazione di una serie di elementi in traccia e sali nell'eluato.	WI 292008, ENV 12506, prEN 13370 (non tutti i parametri sono contemplati)
Solidi disciolti totali (TDS)	Determinazione della quantità totale di frazione che viene disciolta dall'eluente, indice di potenziali rischi di interazione con l'ambiente circostante	N/A
Carbonio organico disciolto (DOC)	Determinare la quantità di componenti organici, che possono a loro volta mobilizzare altri costituenti	prEN 13370

3.2.3 Valutazioni preliminari sul comportamento ambientale delle ceneri di carbone

Vengono di seguito riportate in sintesi alcune valutazioni raccolte durante lo studio di best practice eseguito e ritenute di particolare interesse e rilevanza in relazione al tema oggetto dell'indagine. Esse sono state elaborate da parte di importanti associazioni internazionali e distribuite pubblicamente al fine di promuovere il riutilizzo dei rifiuti secondo modalità ritenute ambientalmente compatibili.

- *Standard ASTM PS 23-95 "Provisional Standard Guide for Use of Coal Combustion Fly Ash in Structural Fills".* (vedi Allegato 1 al rapporto)

Un documento importante cui fare riferimento quale punto di partenza per un giudizio sul comportamento ambientale delle ceneri di carbone utilizzate per impieghi nel settore geotecnico e che può costituire un utile riferimento nella stesura di un documento di best practice sulle modalità per un loro impiego ambientalmente corretto è lo Standard ASTM PS 23-95 "Provisional Standard Guide for Use of Coal Combustion Fly Ash in Structural Fills". Pubblicato nel 1995 e riportato sugli Annual Book of ASTM Standards Vol 04.08., lo standard viene allegato al presente rapporto.
Lo standard considera le modalità di progettazione e di realizzazione dei rilevati strutturali a base di ceneri di carbone suggerendo idonee procedure per la valutazione dei principali aspetti ingegneristici, economici ed ambientali.

Se ne riportano di seguito alcune considerazioni ritenute di particolare rilievo ai fini del presente rapporto.

Al punto 4.3.1.1. dello Standard, in riferimento alla regolamentazione federale americana, si afferma che la USEPA (U. S. Environmental Protection Agency) ha condotto uno studio approfondito sulle ceneri da carbone in cui ha concluso che le caratteristiche e le modalità di gestione delle ceneri non giustificano alcun riferimento alle regolamentazioni sui rifiuti pericolosi e le loro pratiche di riutilizzo appaiono ambientalmente sicure. L'EPA afferma pertanto che "L'Agenzia non ha rilevato alcun danno ambientale associato con l'utilizzazione di larghi volumi di rifiuti derivanti dagli impianti termoelettrici a carbone". Pertanto l'EPA "incoraggia l'utilizzo dei sotto prodotti termoelettrici e sostiene gli Stati impegnati nella promozione del loro impiego in condizioni ambientalmente benefiche".

Il medesimo Standard, al punto 4.3.2.1 *Ground Water Quality* afferma che significative ricerche sono state fatte al fine di valutare e predire potenziali impatti delle ceneri sulle acque di falda. Queste ricerche indicano che metalli come cromo, cadmio, arsenico e selenio sono presenti in tenori molto ridotti nelle ceneri, in forme relativamente insolubili e comunque in concentrazioni simili a quelle riscontrabili in altri materiali per riempimenti.

Si raccomandano tuttavia alcuni fondamentali principi di buona pratica al fine di minimizzare qualsiasi potenziale forma di contaminazione delle acque di falda e superficiali:

- Il progetto e la realizzazione del rilevato strutturale a base di ceneri deve considerare il potenziale impatto sulle acque di falda al fine di assicurare la protezione per l'uomo e l'ambiente. Tale valutazione dovrà prendere in considerazione specifici parametri di progetto, quali il volume e la composizione del rilevato, i possibili fenomeni di infiltrazione, i conseguenti fenomeni di migrazione di elementi inquinanti e di attenuazione per interazione con il suolo. Tali considerazioni dovranno essere condotte nel contesto della attuale qualità delle acque di falda e dei suoi utilizzi attuali e futuri.

  Nel caso di particolari condizioni di tutela, come nel caso di sorgenti o aree protette, sarà necessario valutare preventivamente le caratteristiche di lisciviazione delle ceneri come parte integrante della valutazione dei fenomeni di migrazione ed attenuazione degli inquinanti, per la quale si potrà fare ricorso a modelli numerici geo-idro-chimici e di trasporto dei soluti.
- Il rilevato strutturale a base di ceneri deve essere progettato e realizzato in maniera tale da minimizzare ogni potenziale impatto sulle acque di falda. Ciò deve essere ottenuto mantenendo una separazione tra lo strato di ceneri e le acque di falda ed adottando pratiche capaci di ridurre i quantitativi di acqua capace di infiltrarsi nel rilevato e di scorrere su esso. Questo include:

  - posizionare sempre il rilevato al di sopra del più alto livello stagionale delle acque di falda;
  - stendere e compattare le ceneri in strati sottili al fine di ridurne la permeabilità;
  - adottare criteri di progetto capaci di minimizzare gli afflussi d'acque meteoriche sul rilevato e di accumulo o scorrimento su esso;
  - evitare durante le fasi realizzative l'essiccazione superficiale delle ceneri (che ne riducono le capacità di sviluppo delle resistenze meccaniche);
  - rivestire prontamente il rilevato con strati protettivi (pavimentazioni stradali o terreni vegetali a seconda della sua destinazione d'uso), compresi i suoi fianchi laterali.
- La qualità delle acque superficiali può essere alterata da fenomeni di erosione, sedimentazione e migrazione di specie chimiche provenienti dal rilevato a base di ceneri di carbone per impedire

i quali devono essere scrupolosamente adottate le medesime norme di buona pratica sopra raccomandate in relazione alle acque di falda.

Analogalmente a quanto fatto per la tutela della qualità delle acque, lo Standard prescrive inoltre alcune raccomandazioni utili a prevenire qualsiasi potenziale impatto sulla qualità dell'aria:

- la polverosità delle ceneri deve essere controllata durante la realizzazione del rilevato al fine di evitare dispersioni del materiale. Esse sono normalmente umidificate presso l'impianto di produzione o stoccaggio e trasportate su camion coperti, ciò facilità le operazioni di compattazione e di controllo della polverosità. Devono tuttavia essere previsti dispositivi adatti all'aggiunta di acqua sul sito di costruzione al fine di evitare eventuali fenomeni di rapida essiccazione superficiale dovuta al particolari condizioni meteorologiche (sole, vento).
- in riferimento alla potenziale radioattività delle ceneri, non viene altresì prescritta alcuna particolare raccomandazione ritenendosi il problema non sussistente nonostante i grandi quantitativi di materiale adottati. Le ceneri presentano infatti tassi di radioattività comparabili a quelli di numerosi materiali naturali e da costruzione e, in alcuni casi, alla stessa radioattività naturale del suolo di costruzione. Per quanto riguarda l'emissione di radon essa non è ritenuta motivo di alcuna considerazione nelle applicazioni all'aperto come quelle oggetto dello Standard, potendosi altresì considerare apprezzabile solo in ambienti completamente chiusi con notevoli periodi di accumulo (assenza di ricambi d'aria) e prolungata permanenza da parte dell'uomo.

- *Gas Stream Cleanup Project - R&D facility Facts; U.S. Department of Energy - Environmental Science and Technology Division* (da www.fetc.doe.gov)

Analoghe, positive valutazioni circa la compatibilità ambientale delle ceneri di carbone per impieghi sul territorio vengono riportate anche dal Federal Energy Technology Center - Environmental Science and Technology Division dell'U.S. Department of Energy in una nota di ricerca di cui si richiamano di seguito le conclusioni più significative.

Sono stati condotti test di cessione al fine di determinare la quantità totale ed i tassi di rilascio di elementi in tracce dalle ceneri di carbone al fine di valutarne la compatibilità ambientale. Sono stati utilizzati sette differenti mezzi liscivianti (acqua demi, acido acetico, pioggia artificiale, acqua di falda artificiale, cloruro ferrico, carbonato di sodio e acido solforico) ed eseguite prove lisimetriche su 28 campioni di 20 differenti ceneri per un periodo di campionamento fino a 60 giorni (tassi di percolazione di circa 250 ml/g ad una pressione di circa 10 psi).

I risultati dei test sono riportati nelle successive Figure 6 e 7.

I risultati evidenziano come i rilasci, sebbene variuabili da campione a campione e generalmente dipendenti elemento per elemento dai valori di pH, appaiono bassi. In media, il rilascio degli elementi in tracce, calcolato come massa estratta, è inferiore a 10 mg/kg e la percentuale estratta di ciascun elemento (As, Cu, Ni, Zn, ..) è inferiore al 20 % del suo tenore nel materiale di partenza.

Se ne conclude che i bassi tassi di rilascio misurati indicano che vi è un effetto ambientale trascurabile legato all'utilizzo delle ceneri di carbone.

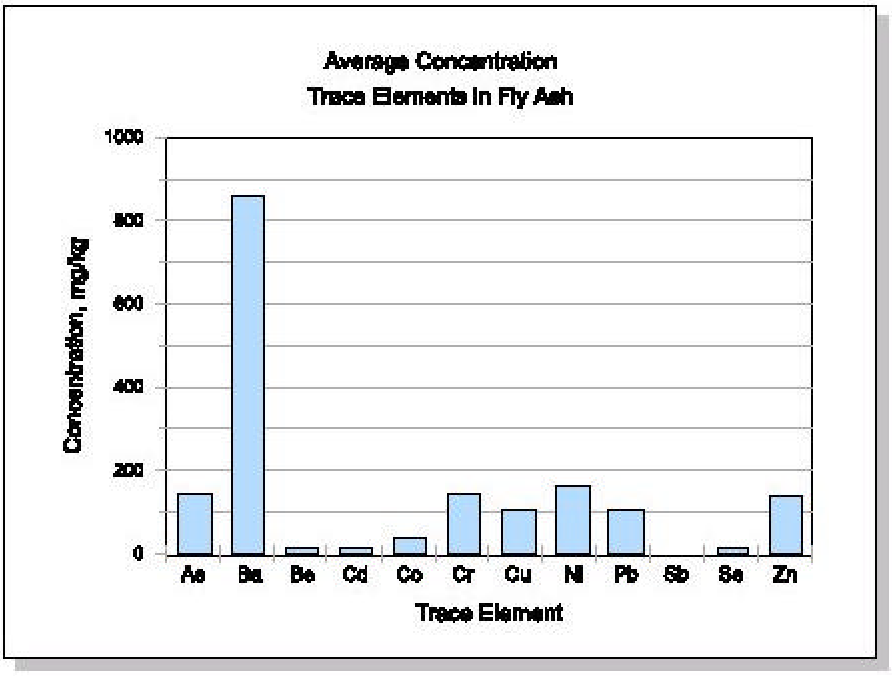


Figura 6 - Concentrazioni medie di elementi in tracce nelle ceneri di carbone

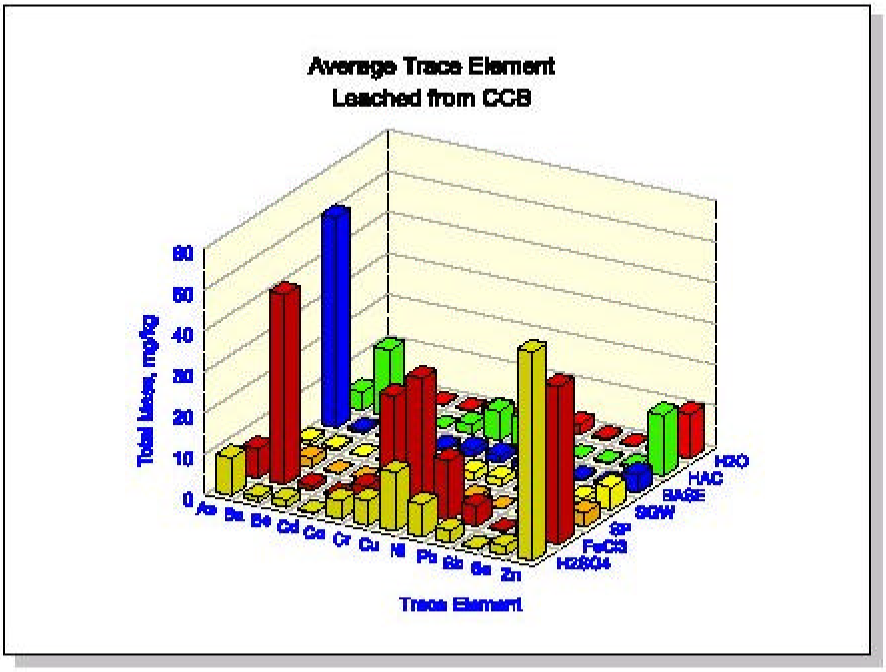


Figura 7 - Concentrazioni medie di elementi in tracce nei prodotti di lisciviazione ottenuti dalle ceneri di carbone secondo differenti metodologie di prova

- *The development of a environmental code of practice for use of pfa as a fill material - United Kingdom Quality Ash Association* (da www.ukqaa.org.uk/Present/CodeFill/)

Lo studio si propone di valutare i potenziali impatti derivanti dall'utilizzo delle ceneri di carbone per la realizzazione di riempimenti e rilevati, facendo riferimento alle singole fasi di trattamento, di seguito riassunte insieme alle principali considerazioni riportate.

Stoccaggio: per le ceneri stoccate all'aperto è necessario impedire le emissioni fuggitive di polveri mediante opportuno condizionamento delle stesse (umidità 10-15% mediante periodico innaffiamento superficiale dei cumuli); è inoltre necessario prevedere vasche o altri dispositivi per il lavaggio delle ruote dei veicoli di manovra all'interno delle aree di stoccaggio o di trasporto in arrivo e uscita da esse per rimuovere il materiale che vi aderisce, impedendone in tal modo la dispersione; è inoltre necessario mantenere pulite le vie di transito e limitare le velocità di percorrenza delle stesse al fine di contenere fenomeni di turbolenza e dispersione di polveri.

Trasporto: non vi sono particolari specificità relative alle ceneri rispetto alle modalità di trasporto di un qualsiasi materiale fine da costruzione; è pertanto necessario umidificare preventivamente le ceneri, far uso di veicoli a tenuta (per evitare le cadute di materiale o il rilascio di acqua drenata), coperti o tendonati (per impedire la dispersione di polveri) ed evitare qualsiasi scarico o sversamento accidentale durante il percorso.

Progettazione dell'opera: in fase di progettazione è necessario prendere in considerazione i potenziali impatti ambientali delle ceneri di carbone prevedendo la preventiva stesa di un opportuno strato di base di pezzatura più grossolana con funzione drenante, capace di impedire risalite capillari di acque interstiziali e proteggendo superiormente l'opera con strati di terreno vegetale o altra natura a seconda delle applicazioni (ad es. il manto bituminoso o in calcestruzzo nel caso delle strade) al fine di prevenire fenomeni di percolazione da parte delle acque meteoriche o di erosione superficiale ad opera del vento o del ruscellamento di acque piovane.

Stesa e compattazione: E' necessario prevenire spolveramenti superficiali prevenendo l'essiccazione superficiale del materiale, specie in condizioni climatiche calde e ventose, spruzzando il materiale con acqua. E' inoltre necessario prevedere una corretta compattazione del rilevato o riempimento in cenere al fine di garantire da subito ridotti valori di permeabilità ($\sim 10^{-7}$m/s).

Comportamento ambientale: Le ceneri si comportano come una terra fine, coesiva e non plastica. Stabilizzata con calce o cemento, in virtù del suo comportamento pozzolanico, sviluppa buone doti di resistenza, portanza e impermeabilità. Costituite essenzialmente da ossidi di silicio, alluminio e ferro, presentano piccole concentrazioni di elementi in tracce inglobati nella matrice vetrosa del materiale e pertanto praticamente non lisciviabili. I prodotti di lisciviazione sono essenzialmente costituiti da idrossido di calcio e solfato di calcio, oltre a piccoli tenori di sodio, potassio e, a bassi valori di pH, magnesio. Nelle successive Tabelle 13, 14 e 15 vengono riportati i dati presentati nello studio in riferimento ai range di composizione tipica degli elementi macro e micro nelle ceneri tal quali e nei suoi prodotti di lisciviazione ottenuti tramite il metodo DIN 38414-S4. I valori reali di rilascio registrati in campo risultano, tuttavia, ulteriormente e di gran lunga inferiori e tutti non critici dal punto di vista ambientale, in virtù della bassa permeabilità che il materiale esibisce in opera a seguito delle operazioni di compattazione e dello sviluppo della reazione pozzolanica. A sostegno di ciò vengono riportati i risultati di Tabella 16 relativi a valori di lisciviazione da stoccaggi reali di ceneri.

Evidenziando infine esempi di ricca rivegetazione e completo reinserimento paesaggistico di rilevati e riempimenti realizzati con ceneri di carbone, se ne conclude l'evidenza dell'inesistenza di problemi ambientali legati al loro uso sul territorio.
Pur tuttavia, a maggior tutela dell'ambiente, si suggeriscono e raccomandano le seguenti procedure di controllo:

- monitorare le caratteristiche di lisciviabilità delle ceneri utilizzando metodi standardizzati, con frequenza almeno annuale da ogni centrale termoelettrica di provenienza (senza necessità di ulteriori verifiche a meno di significativi mutamenti nelle caratteristiche dei combustibili utilizzati);
- se le ceneri sono destinate all'uso in aree di particolare sensibilità ambientale (aree protette, prossimità di corsi d'acqua) è necessario condurre analisi di conducibilità e pH con periodicità da concordare tra fornitore e destinatario.

Tabella 13 - Intervalli di concentrazione dei macro-elementi nelle ceneri
(da "The development of an environmental code of practice for use of pfa as a fill material" UKQAA)

Element	Typical range of values for pfa
Silicon (% as SiO_2)	48 – 52
Aluminium (% as Al_2O_3)	24 – 32
Iron (% as Fe_2O_3)	7 – 15
Calcium (% as CaO)	1.8 – 5.3
Magnesium (% as MgO)	1.2 – 2.1
Sodium (% as Na_2O)	0.8 – 1.8
Potassium (% as K_2O)	2.3 – 4.5
Titanium (% as TiO_2)	0.9 – 1.1
Chloride (% as Cl)	0.01 – 0.02*
Loss on ignition (%)	3 – 20
Sulfate (% as SO_3)	0.35 – 1.7
Free calcium oxide (%)	<0.1 – 1.0
Water soluble sulfate (g/L as SO_4)	1.3 – 4.0
2:1 water solid extract	
pH	9 – 12

*** Excludes seawater conditioned material**

Tabella 14 -Intervalli di concentrazione degli elementi in tracce nelle ceneri
(da "The development of an environmental code of practice for use of pfa as a fill material" UKQAA)

	Typical range of results
Arsenic	4 to 109
Boron	5 to 310
Barium	0 to 36,000
Cadmium	<1.0* to 4
Chloride	0 to 2,990
Cobalt	2 to 115
Chromium	97 to 192
Copper	119 to 474
Fluoride	0 to 200
Mercury	<0.01* to 0.61
Manganese	103 to 1,555
Molybdenum	3 to 81
Nickel	108 to 583
Phosphorus	372 to 2,818
Lead	<1* to 976
Antimony	1 to 325
Selenium	4 to 162
Tin	933 to 1,847
Vanadium	292 to 1,339
Zinc	148 to 918

mg/kg
* Indicates value below detection limit

Tabella 15 - Analisi lisciviati da test di cessione sulle ceneri leggere
(da "The development of an environmental code of practice for use of pfa as a fill material" UKQAA)

DIN38414-S4 method

Typical range of leachable elements for UK PFA (mg/L except pH)			
Aluminium	<0.1* to 9.8	Manganese	<0.1*
Arsenic	<0.1*	Molybdenum	<0.1* to 0.6
Boron	<0.1* to 6	Sodium	12 to 33
Barium	0.2 to 0.4	Nickel	<0.1*
Calcium	15 to 216	Phosphorus	<0.1* to 0.4
Cadmium	<0.1*	Lead	<0.2*
Chloride	1.6 to 17.5	Sulfur	24 to 510
Cobalt	<0.1*	Antimony	<0.01*
Chromium	<0.1*	Selenium	<0.01* to 0.15
Copper	<0.1*	Silicon	0.5 to 1.5
Fluoride	0.2 to 2.3	Tin	<0.1*
Iron	<0.1*	Titanium	<0.1*
Mercury	<0.01*	Vanadium	<0.1* to 0.5
Potassium	1 to 19	Zinc	<0.1*
Magnesium	<0.1* to 3.9	pH	7 to 11.7

Tabella 16 - Intervalli di composizione nel prodotto di lisciviazione da stoccaggi reali di ceneri in mucchio

(da "The development of an environmental code of practice for use of pfa as a fill material" UKQAA)

Leachates from stockpile pfa...

Typical range of leachable elements, 10 samples, single source (mg/L except pH)			
Bed Volume	1	Molybdenum	0.15 to 0.88
pH	8.1 -8.8	Sodium	5 to 44
Aluminium	<0.1* to 0.5	Nickel	<0.01*
Arsenic	0.06 to 0.16	Lead	<0.01*
Boron	1.8 to 4.3	Tin	<0.01*
Calcium	33 to 250	Titanium	<0.01*
Cadmium	<0.005*	Vanadium	0.22 to 0.55
Cobalt	<0.01*	Zinc	<0.01*
Chromium	0.02 to 0.06	Nitrogen	0.2 to 1
Copper	<0.01*	Phosphorus	<0.1*
Iron	<0.01*	Sulfur	15 to 70
Mercury	<0.001*	Chloride	5 to 9
Potassium	5 to 29	Fluoride	<0.1*
Magnesium	16 to 100	Selenium	0.04 to 0.16
Manganese	<0.01*	Antimony	<0.2

* Indicates value below detection limit

4. Conclusioni

Lo studio condotto ha mirato, da un lato, a delineare una sintesi degli aspetti tecnici relativi al riutilizzo delle ceneri di carbone nella realizzazione di rilevati, riempimenti e strati di fondazione, e, dall'altro, a verificare il livello di diffusione ed il quadro normativo e legislativo, nazionale ed internazionale, relativi a questa forma di reimpiego.

Gli aspetti tecnici analizzati hanno consentito di individuare le modalità di riutilizzo e le condizioni finali del materiale in opera (modalità di stoccaggio, trasporto, posa in opera e, ancora, materiali in miscela, densità, permeabilità, pH, resistenze meccaniche, ecc. del prodotto finale). Da queste condizioni dipendono le modalità di interazione delle ceneri con l'ambiente circostante. Esse appaiono essenzialmente riconducibili al potenziale rilascio di metalli pesanti dal prodotto finale in opera a seguito di fenomeni di lisciviazione. La loro determinazione è indispensabile per una corretta simulazione del materiale e del suo comportamento nella successiva fase di verifica sperimentale in laboratorio.

Per quanto attiene all'analisi del quadro internazionale, dal contenuto del rapporto si evidenzia chiaramente come l'impiego in campo geotecnico delle ceneri di carbone sia una pratica consolidata da tempo, che ha avuto innumerevoli applicazioni su vasta scala in tutti i principali paesi in cui esse sono prodotte.
Significativi quantitativi di ceneri di carbone vengono attualmente destinati a tale reimpiego in molti Paesi Europei (Francia, Germania, Inghilterra), così come negli Usa, in Giappone, in Canada.
Queste applicazioni hanno trovato conferma nella stesura di linee guida che ne evidenziano i vantaggi tecnici, economici ed ambientali, anche a seguito di prolungati periodi di osservazione su applicazioni in piena scala.
Studi condotti dall'EPA (U.S. Environmental Protection Agency) confermano la loro compatibilità ambientale, pur nel rispetto di raccomandazioni di buona pratica e di prevenzione nei confronti di possibili fenomeni di inquinamento del suolo e delle acque (superficiali e di falda).
Standard tecnici sono stati pubblicati a livello nazionale ed internazionale e sono in corso di approvazione anche in Europa a livello comunitario (CEN TC 227) a riprova dell'ormai consolidato atteggiamento nei confronti di tali forme di riutilizzo delle ceneri di carbone.
Se da un lato appare quindi generalmente confermato il giudizio di accettabilità di tale destinazione d'uso delle ceneri di carbone e questo risulti sempre più consolidato dal punto di vista della normativa tecnica di settore, appaiono tuttavia ancora incerti i criteri di analisi e gli strumenti legislativi per attestarne la compatibilità ambientale.
La complessità del comportamento di un generico materiale, di un rifiuto e nella fattispecie delle ceneri, all'interno di una matrice idrogeologica con specifiche caratteristiche bio-fisico-chimiche è infatti di difficile determinazione e previsione. Questa complessità è testimoniata dalla ingente attività normativa portata avanti a livello comunitario dal CEN TC 292 "Characterisation of wastes" richiamata dallo studio condotto. Facendo riferimento alle proposte di norma avanzate nell'ambito di tale Comitato verranno individuate le prove e le modalità di esecuzione delle stesse più idonee ad attestare il comportamento delle ceneri, a cui verrà fatto riferimento nelle successive verifiche sperimentali di laboratorio previste nell'ambito del progetto di ricerca.

ALLEGATO 1:

Standard ASTM PS 23-95

"Guide for the Use of Coal Combustion Fly Ash in Structural Fills"

ALLEGATO 2:

"Fly Ash Facts for Highway Engineers"

(Rep. FHWA-SA-94-081) U.S. Dept. of Transportation, Fed. Highway Adm., USA 1995

ALLEGATO 3:

UKQAA Technical Datasheets:

2 - Fill: How PFA/fly ash can be used for fill application

6.0 - FABM's: Fly Ash Bond Mixtures for road and airfield pavements

6.1 - GFA's: Lime and cement bound granular fly ash mixtures for use as a sub-base and road base layer

6-4 - Fly ash in CBM: How fly ash can be incorporated in cement bound mixtures

Environment: PFA/fly ash and environmental considerations

ALLEGATO 4:

Proposta di norma tecnica comunitaria pr EN (TC 227 WI 190)
"Unbound and hydraulically bound mixtures - Part 3: Fly ash bound mixtures - Definitions, composition, classification"

ALLEGATO 5:

Proposta di norma pr EN (TC 227 WI 191)
"Unbound and hydraulically bound mixtures - Part 4: Fly ash for hydraulically bound mixtures - Definitions, composition, classification"

Scheda per la registrazione dei rapporti tecnici interni

<table>
<tr><td colspan="2">ENEL Produzione SpA - Ricerca
Litoranea S.na Brindisi-Casalabate
Località Cerano - C.P. n. 28
72020 TUTURANO (BR)
Tel. + 39-0831/535.1 Fax + 39-0831/535-570</td><td colspan="2">Progetto: COMPA
Sotto Progetto: PERFORMA
Attività: " Linee guida per procedure di caratterizzazione"</td><td colspan="2">Contratto n.
N. rapp.: ENELP/RIC/RT-2001/129/0-IT+RA.RIC.BR
Codice interno:
Anno di emissione: 2001</td></tr>
<tr><td colspan="6">Titolo del rapporto
Analisi di best practice per la predisposizione di linee guida finalizzate a promuovere l'utilizzo delle ceneri di carbone in campo geotecnico.</td></tr>
<tr><td colspan="3">Autori (Cognome, Nome)
Belz, Giulio</td><td colspan="3">Gruppo di lavoro/Organizzazione di appartenenza (esterni)
Belz Giulio, Aldo Giove, Miglietta Giuseppe</td></tr>
<tr><td colspan="6">Riassunto (in lingua italiana) max 1500 caratteri
Obiettivo dell'attività è la predisposizione di linee guida “tematiche“ per la qualificazione ambientale di rifiuti di particolare interesse del Settore Elettrico in relazione a specifiche forme di potenziale valorizzazione e riutilizzo degli stessi attualmente non contemplate dalla relativa legislazione (D.M. 5/2/98) al fine di una sua successiva possibile integrazione. Quale obiettivo specifico, il presente Rapporto si propone di valutare la possibilità di utilizzare, in condizioni tecnicamente ed ambientalmente sicure, le ceneri di carbone per la realizzazione di rilevati e sottofondi stradali. Esso intende fornire una analisi di best practice relativa a tali forme di reimpiego e, in particolare,:
▪ presenta una sintesi delle caratteristiche chimico-fisiche delle ceneri di carbone e dei loro settori di riutilizzo;
▪ evidenzia i principali dati nazionali ed internazionali di produzione e destinazione;
▪ valuta l’attuale quadro legislativo e normativo, nazionale ed internazionale;
▪ richiama i principali vantaggi tecnici legati alle forme di riutilizzo più consolidate;
▪ analizza in maggior dettaglio gli aspetti tecnici relativi all'impiego delle ceneri di carbone per la realizzazione di: a) rilevati strutturali, b) sottofondi stradali, c) riempimenti, al fine di confermare la validità tecnica di tali applicazioni e di valutarne le modalità e le condizioni di interazione con l'ambiente;
▪ sintetizza preliminarmente i risultati e le considerazioni sulla compatibilità ambientale delle ceneri per impieghi geotecnici così come emergono dall'indagine di best practice;
▪ riassume il quadro normativo in corso di definizione a livello Europeo per la caratterizzazione ambientale dei rifiuti, con particolare riferimento all'attività portata avanti nell'ambito del comitato tecnico CEN TC 292 "Characterisation of wastes".
Riassunto scritto da: Giulio Belz</td></tr>
<tr><td colspan="6">Parole chiave (in lingua italiana)
Ceneri di carbone, riutilizzo, impieghi stradali</td></tr>
<tr><td colspan="2">Vincoli di riservatezza:</td><td colspan="2">Lingua: Italiano e Inglese
N. pagine: 163 p.</td><td colspan="2">Consegnato da:</td></tr>
<tr><td>N. copie emesse:</td><td colspan="5">Note</td></tr>
</table>

AMERICAN SOCIETY FOR TESTING AND MATERIALS
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If not listed in the current combined index, will appear in the next edition.

Provisional Standard Guide for Use of Coal Combustion Fly Ash in Structural Fills[1]

This standard is issued under the fixed designation PS 23; the number immediately following the designation indicates the year of original adoption.

1. Scope

1.1 This provisional guide covers the design and construction of engineered structural fills using coal combustion fly ash. This provisional guide suggests procedures for consideration of engineering, economic, and environmental factors in the development of fly ash structural fills.

1.2 The utilization of coal combustion fly ash under this provisional guide is a component of a pollution prevention program; Guide E 1609 describes pollution prevention activities in more detail. Utilization of coal combustion fly ash in this manner conserves land, natural resources, and energy.

1.3 This provisional guide applies only to fly ash produced solely by the combustion of coal. It does not apply to bottom ash, boiler slag or mixtures of fly ash, bottom ash or boiler slag.

1.4 The testing, engineering, and construction practices for fly ash structural fills are similar to generally accepted practices for engineered soil fills. Fly ash structural fills should be designed by a qualified professional engineer.

1.5 Regulations governing the use of fly ash vary by state. The user of this provisional standard has the responsibility to determine and comply with applicable regulations.

1.6 The values stated in inch-pound units are to be regarded as the standard. The SI units given in parentheses are for information only.

1.7 Provisional standards[2] achieve limited consensus through approval of the sponsoring subcommittee.

1.8 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

C 188 Test Method for Density of Hydraulic Cement[3]
C 311 Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in Portland-Cement Concrete[4]
C 595 Specification for Blended Hydraulic Cements[3]
D 75 Practice for Sampling Aggregates[5]
D 420 Guide to Site Characterization for Engineering, Design, and Construction Purposes[6]
D 422 Test Method for Particle-Size Analysis of Soils[6]
D 653 Terminology Relating to Soil, Rock, and Contained Fluids[6]
D 698 Test Method for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft^3 (600 kN-m/m^3))[6]
D 854 Test Method for Specific Gravity of Soils[6]
D 1195 Test Method for Repetitive Static Plate Load Tests of Soils and Flexible Pavement Components, for Use in Evaluation and Design of Airport and Highway Pavements[6]
D 1196 Test Method for Nonrepetitive Static Plate Load Tests of Soils and Flexible Pavement Components, for Use in Evaluation and Design of Airport and Highway Pavements[6]
D 1452 Practice for Soil Investigation and Sampling by Auger Borings[6]
D 1556 Test Method for Density and Unit Weight of Soil In Place by the Sand-Cone Method[6]
D 1557 Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56 000 ft-lbf/ft^3 (2700 kN-m/m^3))[6]
D 1586 Test Method for Penetration Test and Split-Barrel Sampling of Soils[6]
D 1883 Test Method for CBR (California Bearing Ratio) of Laboratory-Compacted Soils[6]
D 2166 Test Method for Unconfined Compressive Strength of Cohesive Soil[6]
D 2167 Test Method for Density and Unit Weight of Soil in Place by the Rubber Balloon Method[6]
D 2216 Test Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock[6]
D 2435 Test Method for One-Dimensional Consolidation Properties of Soils[6]
D 2850 Test Method for Unconsolidated, Undrained Compressive Strength of Cohesive Soils in Triaxial Compression[6]
D 2922 Test Methods for Density of Soil and Soil-Aggregate in Place by Nuclear Methods (Shallow Depth)[6]
D 3080 Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions[6]
D 3550 Practice for Ring-Lined Barrel Sampling of Soils[6]
D 3877 Test Methods for One-Dimensional Expansion, Shrinkage, and Uplift Pressure of Soil-Lime Mixtures[6]

[1] This provisional guide is under the jurisdiction of ASTM Committee E-50 on Environmental Assessment and is the direct responsibility of Subcommittee E50.03 on Pollution Prevention, Reuse, Recycling, and Environmental Efficiency. Current edition approved Aug. 15, 1995. Published October 1995.
[2] Provisional standards exist for two years subsequent to the approval date.
[3] *Annual Book of ASTM Standards*, Vol 04.01.
[4] *Annual Book of ASTM Standards*, Vol 04.02.
[5] *Annual Book of ASTM Standards*, Vol 04.03.
[6] *Annual Book of ASTM Standards*, Vol 04.08.

D 4318 Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils[6]
D 4429 Test Method for Bearing Ratio of Soils in Place[6]
D 4643 Test Method for Determination of Water (Moisture) Content of Soil by the Microwave Oven Method[6]
D 4959 Test Method for Determination of Water (Moisture) Content of Soil by Direct Heating Method[7]
D 4972 Test Method for pH of Soils[7]
D 5084 Test Method for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter[7]
D 5239 Practice for Characterizing Fly Ash for Use in Soil Stabilization[7]
E 1527 Practice for Environmental Site Assessments: Phase I Environmental Site Assessment Process[8]
E 1528 Practice for Environmental Site Assessments: Transaction Screen Process[8]
G 51 Test Method for pH of Soil for Use in Corrosion Testing[7]
G 57 Test Method for Field Measurement of Soil Resistivity Using the Wenner Four-Electrode Method[9]

2.2 *AASHTO Standards:*[10]
T 288 Determining Minimum Laboratory Soil Resistivity
T 289 Determining pH of Soil for Use in Corrosion Testing
T 290 Determining Water Soluble Sulfate Ion Content in Soil
T 291 Determining Water Soluble Chloride Ion Content in Soil

2.3 *EPA Standard:*[11]
9045 Soil pH

3. Terminology

3.1 *Definitions*—Definitions are in accordance with Terminology D 653.

3.2 *Descriptions of Terms Specific to This Standard:*

3.2.1 *baghouse*—a facility constructed at some coal-fired power plants consisting of fabric filter bags that mechanically trap particulate (fly ash) carried in the flue gases.

3.2.2 *beneficial use*—projects promoting public health and environmental protection, offering equivalent success relative to other alternatives, and preserving natural resources.

3.2.3 *bottom ash*—the slag deposited on the heat-absorbing surfaces of a coal-fired furnace that subsequently falls to the furnace bottom.

3.2.4 *cementitious fly ash*—a fly ash usually derived from subbituminous and lignite coals that contains sufficient calcium and other compounds to induce a cementitious reaction in the presence of water.

3.2.5 *drainage blanket*—a uniform layer of permeable material (such as sand, crush stone, or bottom ash) installed with properly designed filter media at the base of a structural fill to maintain the fill in a drained condition.

3.2.6 *electrostatic precipitator*—a facility constructed at some coal-fired power plants to remove particulate (fly ash) from the flue gas by producing an electric charge on the particles to be collected and then propelling the charged particles by electrostatic forces to collecting curtains.

3.2.7 *fly ash*—finely divided residue that results from the combustion of coal.

DISCUSSION—This definition of *fly ash* does not include, among other things, the residue resulting from: (*1*) the burning of municipal garbage or any other refuse with coal; or (*2*) the injection of limestone or lime directly into the boiler or flue for sulfur removal; or (*3*) the burning of industrial or municipal garbage in incinerators commonly known as *incinerator ash*.

3.2.8 *internal erosion*—piping; the progressive removal of soil particles from a mass by percolating water, leading to the development of channels.

3.2.9 *structural fill*—an engineered fill with a projected beneficial end use that is typically constructed in layers of uniform thickness and compacted to a desired unit weight (density) in a manner to control the compressibility, strength, and hydraulic conductivity of the fill.

4. Significance and Use

4.1 *General*—Coal fly ash can be an effective material for the construction of engineered, structural fills. Fly ash may be used as: structural fill for building sites; embankments for highways and railroads, dikes, and levees; for ecoscreens; and in any other application requiring a compacted fill material. Its low unit weight, relatively high shear strength, ease of handling, and compaction all make it useful as a fill material. Fly ash may be a cost-effective fill material in many areas because it is available in bulk quantities and reduces the expenditures required for the purchase, permits, and operation of a soil borrow pit. Also, because fly ash is an abundantly produced by-product, its use in large-volume applications such as in the construction of structural fills provides an outlet for material, provided that the fly ash is environmentally and geotechnically suitable for the desired use.

4.1.1 Fly ash is a fine-grained residue removed from the flue gases at electric generating stations by electrostatic precipitators and baghouses. It is typically stored dry in silos or sluiced into holding bins or lagoons, where it may be commingled with bottom ash or boiler slag. Siloed fly ash that is not utilized in commerce is usually landfilled.

4.1.2 Electric generating stations burn either bituminous, subbituminous, or lignite coal. All coal fly ashes are pozzolanic, however, certain subbituminous and lignite ashes may contain higher amounts of calcium oxide and exhibit greater cementitious properties. The laboratory testing and design considerations for cementitious and noncementitious fly ashes vary in some instances. Guidance is provided in Sections 6 through 9.

4.2 *Engineering Properties and Behavior*—Fly ash is typically a relatively uniform, silt-sized material and behaves similarly to natural, cohesionless silty soils, although the

[7] *Annual Book of ASTM Standards*, Vol 04.09.
[8] *Annual Book of ASTM Standards*, Vol 11.04.
[9] *Annual Book of ASTM Standards*, Vol 03.02.
[10] Interim Specifications for Transportation Materials and Methods of Sampling and Testing, Part II, AASHTO, 444 North Capitol St., N.W., Suite 225, Washington, DC 20001.
[11] Test Methods for Evaluating Solid Waste, Physical/Chemical Methods, SW-846, Third Edition, 1986, Office of Solid Waste and Emergency Response, Washington, DC 20460.

cementitious ashes will solidify over time. However, fly ash has a lower specific gravity than most natural soils and primarily consists of spherical particles. These qualities, along with its cohesionless nature (for non-cementitious ash), result in certain properties and behavior that differ from other commonly used fill materials.

4.2.1 *Low Unit Weight*—Fly ash has a low dry unit weight, typically about 50 to 100 pcf (8 to 16 kN/m^3). The low unit weight of fly ash fills will reduce the load on weak layers or zones of soft foundation soil. This property is advantageous on sites where poor foundation soils exist or in landslide-prone areas. The low unit weight of fly ash will also reduce transportation costs since less tonnage of material is hauled to fill a given volume.

4.2.2 *Low, Rapid Compressibility*—Post-construction embankment settlement or deformation of fly ash structural fills, or both, is minimal due to the high strength and relatively permeable nature of densely compacted fly ash. Fly ash, being several orders of magnitude more permeable than clayey soils typically exhibits small amounts of time-dependent, post-construction consolidation. This is because of the more rapid dissipation of excess pore water pressures, and thus, most of the embankment settlement or deformation occurs due to elastic deformation of the fly ash, rather than by classical consolidation. Most deformation due to the mass of the fill or structure thereon generally occurs during construction.

4.2.3 *Relatively High Shear Strength*—The shear strength of non-cementitious fly ash is primarily the result of internal friction. Typical values for angles of internal friction are higher than many natural soils. These ashes are non-cohesive and although it may appear cohesive in a partially saturated state, this effect is completely lost when the material is either completely dried or saturated. Cementitious ashes experience a cementing action that is measured as cohesion and increases with time. The overall shear strength of self-hardening fly ashes is usually higher than most natural soils.

4.2.4 *Liquefaction and Frost Heave*—Although fine-grained and non-cohesive materials such as fly ash are susceptible to liquefaction and frost heave when saturated, these problems are readily controlled. Because of its sensitivity to moisture, it is standard practice to design fly ash fills to be well drained. Typically, drainage blankets to provide internal drainage and serve as a capillary barrier are included at the base of fills. Also, locating fills in areas where they are not subject to saturation or infiltration by surface or ground water is normally considered in design. Cementitious fly ashes are not susceptible to liquefaction.

4.2.5 *Internal Erosion (Piping)*—Non-cementitious fly ash is subject to internal erosion due to its fine-grained, non-cohesive nature. Internal erosion can be controlled by providing adequate surface water controls to minimize infiltration and by providing internal drainage when warranted.

4.2.6 *Swelling*—Some cementitious fly ashes may swell with time and require the use of nonstandard test procedures and complex engineering analyses. Such ashes are beyond the scope of this provisional guide.

4.3 *Environmental Considerations.*

4.3.1 *Regulatory Framework:*

4.3.1.1 *Federal*—The U.S. Environmental Protection Agency (USEPA) has completed a study of coal combustion ash for the U.S. Congress and has issued a formal regulatory determination **(1, 2)**.[12] The Environmental Protection Agency (EPA) has concluded that the characteristics and management of coal ash do not warrant hazardous waste regulation and that ash utilization practices appear to be safe. The EPA stated "The agency has not found any environmental damages associated with utilization of large-volume coal-fired utility wastes" **(3)**. Therefore, the EPA "encourages the utilization of coal combustion by-products and supports State efforts to promote utilization in an environmentally beneficial manner" **(3)**. There is currently no regulatory program at the Federal level that regulates the use of fly ash in structural fills. The National Environmental Policy Act (NEPA) requires environmental assessments in cases of major federal actions significantly affecting the environment, and this requirement may apply to some structural fill projects, such as federal highway projects, undertaken by federal agencies or with federal funding.

4.3.1.2 *State and Local*—There is considerable variation in state-mandated permitting and other regulatory requirements. Some states have specific beneficial use provisions, while other states have no regulations addressing beneficial use. In many states, fly ash is classified as an industrial or special waste, or both, and no distinction is made between discarded or utilized ash. The U.S. Department of Energy has recognized that this "waste" classification often adversely influences state regulatory agency acceptance and approval of high-volume utilization of fly ash and results in application of inappropriate waste disposal requirements **(4)**. To overcome this barrier, it is important to characterize completely both the ash and the environmental setting in which the project will be undertaken and to manage any environmental impacts associated with the project. Although the NEPA strictly applies only to federally funded projects, many states have similar mechanisms for assessing the environmental impacts of non-federal projects.

4.3.2 *Water Quality:*

4.3.2.1 *Ground Water*—Considerable research has been done on assessment and prediction of potential impacts of fly ash on groundwater **(5–17)**. This research indicates that metals such as chromium, cadmium, arsenic, and selenium are present in very low concentrations in most but not all fly ashes and are generally present in relatively insoluble forms. These metals may occur in other natural fill materials in similar concentrations. Other more soluble chemicals (for example, calcium, sulfate, and boron) present in fly ash are also present in similar concentrations in natural groundwater systems and soil pore water.

(*1*) The design and construction of fly ash structural fills should consider potential groundwater impacts to ensure protection of human health and the environment. Such an assessment may take into account project specific considerations such as volume and composition of fill materials, rates of infiltration, and constituent migration and attenuation. These considerations would be evaluated within the context

[12] The boldface numbers in parentheses refer to the list of references at the end of this standard.

of existing groundwater quality and present and future groundwater uses. Where protection of groundwater is a special concern, as with wellhead or groundwater protection areas, the leaching characteristics of the fly ash should be evaluated as part of an assessment of constituent migration and attenuation. Computer-based geohydrochemical and solute transport models can be useful tools in performing this evaluation.

(*2*) Fly ash structural fills should be designed and constructed to minimize groundwater impacts by maintaining a separation between the fly ash and groundwater, and by engineering and construction practices that reduce the amount of infiltration of rainfall and run-on. These include: placing the fly ash above the seasonal high groundwater table; placing and compacting the fly ash in thin layers to reduce the hydraulic conductivity (permeability) of the fly ash; employing effective stormwater management controls to maximize runoff and minimize run-on; grading exposed ash surfaces to quickly drain; and promptly covering the fly ash with a vegetated soil layer, pavement, structure, or other form of permanent cover. Fly ash structural fills are covered on the outer slopes and the top with natural soils to reduce infiltration and to prohibit erosion of the fly ash.

4.3.2.2 *Surface Water*—As with other fill materials, fly ash structural fills may affect surface water bodies through the processes of erosion, sedimentation, and chemical migration. The engineering and construction practices recommended to minimize groundwater impacts are also effective in controlling effects on surface waters. These include: placing the fly ash above the seasonal high groundwater table; placing and compacting the fly ash in thin layers to reduce the permeability of the fly ash; employing effective stormwater management controls to maximize run-off and minimize run-on; grading exposed ash surfaces to quickly drain; and promptly covering the fly ash with a vegetated soil layer, pavement, structure, or other form of permanent cover.

4.3.3 *Air Quality:*

4.3.3.1 *Radionuclides*—Certain radioactive elements are known to occur naturally in coal ash and other fill materials. Exposure to these elements could therefore be greater where high volumes of coal fly ash are deposited. In most cases, emissions from the ash are not likely to exceed the naturally occurring ambient emissions. Radon emissions are generally considered a potential health hazard only where they may be trapped in a structure occupied by people for many hours a day. The model standards and techniques for controlling radon in accordance with Ref **(18)** are recommended for new building construction.

4.3.3.2 *Dust Control*—Dusting must be controlled during placement of fly ash in structural fills in order to avoid nuisance complaints and to protect worker safety. Noncementitious fly ash is usually conditioned with water at the plant and hauled in covered dump trucks with tightly sealed tailgates. Cementitious fly ash is typically hauled in pneumatic tank trucks. Conditioning the fly ash prior to placement to the specified water content to facilitate compaction will control dusting during the placement operation. Water trucks should be employed as needed during construction to prevent fugitive dust due to equipment operation, wind, and rapid drying of the fly ash surface.

4.4 *Economic Benefits*—The use of fly ash in structural fill can have many economic benefits. These benefits are affected by local and regional factors including production rates, processing and handling costs, transportation costs, availability of competing materials, environmental concerns, and the experience of materials specifiers, design engineers, purchasing agents, contractors, legislators, regulators, and other professionals.

4.4.1 One benefit is the elimination of the long-term landfill disposal costs. Because fly ash is an abundant by-product, its use in large-volume applications provides a utilization option for excess material that would otherwise be disposed. Landfill disposal costs can be very expensive depending on location, and the elimination of these costs can be beneficial to producers and ratepayers. Another benefit is increased revenues from the use of coal fly ash as an engineering material. Fly ash can be a cost-effective, alternative fill material, competing with virgin, processed, or manufactured materials. In many areas, it is available in bulk quantities and requires minimal expenditures for the purchase, permits, and operations as a soil borrow pit. Finally, the use of fly ash in structural fills can be an important component of a corporate pollution prevention plan.

5. Site Characterization

5.1 *General*—The siting and design of a fly ash structural fill requires the same characterization of site conditions that is typically required of earthwork construction projects of similar size. An investigation of the geologic and hydrologic conditions at the site is required to determine design parameters for the structural fill. In addition, consideration of environmental resources at or near the site is required to avoid or minimize negative environmental consequences. Practices E 1527 and E 1528 may be applied whenever a real estate transaction is involved.

5.2 *Geologic and Hydrologic Investigation*—Subsurface conditions at the site must be understood. This typically involves a review of available information about the site, a site reconnaissance by a geologist or geotechnical engineer, and extraction of soil and rock samples from the subsurface for classification and testing. Guide D 420 provides guidance for conducting subsurface investigations.

5.3 *Environmental Resources*—Many sensitive environmental resources such as wetlands, floodplains, rare and endangered species, and cultural resource areas are afforded protection by Federal, state, and local regulations and ordinances. Appropriate action should be taken to comply with the requirements of the regulatory agency having jurisdiction at the structural fill site.

6. Laboratory Test Procedures

6.1 *General*—Laboratory testing of the proposed fill materials is needed to determine and confirm material properties for design. Test results also provide documentation that may be requested or required by site owners and regulatory agencies. The tests to be conducted should be determined by a qualified engineer based on site conditions, knowledge of the fly ash and its generation, end use, and local environmental considerations.

6.2 *Sampling and Handling*—Sampling fly ash sources for testing purposes should conform to Practice D 75 for stockpiles and active production facilities. Sampling of storage areas and especially sluiced fly ash storage areas should account for variations in fly ash properties. Guide D 420 with sample extraction conducted in accordance with Practice D 1452, Test Method D 1586, or Practice D 3550, as appropriate, should be considered. Proper laboratory protocols for handling fine material should be followed.

6.3 *Physical and Engineering Characteristics*—Several standard tests developed for soils may be used to determine fly ash properties for use in structural fills. These methods define physical and engineering parameters for use in design, construction control, and for comparison to other materials.

6.3.1 *Grain-Size Distribution*—Test Method D 422 is commonly used for determining the grain size distribution of fly ash. For fly ash a substantial portion of the material will be finer than the No. 200 sieve and hydrometer analyses will also be required. Distilled water is used in the hydrometer test with a deflocculating agent added to prevent fly ash from forming flocs. Cementitious fly ashes may require use of alcohol or other nonreactive solution in place of the standard solution used. Fly ash often has a relatively uniform particle size and precautions against overloading sieves are warranted. Specimen loss through dusting can also be a problem. Ash specific gravity may vary with particle size. Specific gravity values used in hydrometer analyses should be appropriate to the portion of the sample being tested.

6.3.2 *Specific Gravity*—Test Method D 854 is normally used for fly ash. For some fly ash samples a significant portion of the particles may have a density less than water and float. Agitation of the slurry may be needed to keep the particles in suspension so that the average specific gravity can be obtained. Alternately for these ashes and cementitious fly ashes, Test Method C 188, which uses kerosene as the fluid, may be used.

6.3.3 *Water Content*—Test Method D 2216 is normally used for fly ash. For cementitious fly ashes, lowering the drying temperature to 140°F (60°C) may be considered to avoid driving off the water of hydration.

6.3.4 *Compaction (Moisture-Unit Weight Relationship)*—Test Methods D 698 or D 1557 may be used depending on the end use. Fly ashes often have optimum water contents that range from 12 to approximately 25 %, a relatively high value for silt-sized materials.

6.3.5 *Strength*—Test Method D 3080 is often used to determine the frictional strength parameters of compacted fly ash specimens under drained conditions. This test is preferred because it models the drained conditions that typically exist in a structural fill constructed of fly ash. When using Test Method D 3080 the method is modified in that the shear box is not to be filled with water as required by 9.8 of Test Method D 3080. Test Method D 2850 is to be used if the as-constructed strength appears to be of design concern due to the site conditions, loading conditions, or the fill height. Specimens tested for strength parameters shall be compacted to the unit weights and water contents required by the project compaction requirements.

6.3.5.1 Cementitious fly ashes are generally tested in unconfined compression at various ages using Test Method D 2166 to evaluate short-term and long-term strength development.

6.3.6 *Hydraulic Conductivity*—Test Method D 5084 is commonly used to determine the hydraulic conductivity of saturated fly ash. Hydraulic conductivity is used to estimate the quantity of infiltration for designing underdrains.

6.3.7 *Compressibility*—Samples should be prepared at the degree of compaction specified for construction and at the optimum water content determined by the compaction test. This is because fly ash tends to lose surface stability in the field when compacted at water contents greater than the optimum for compaction. Test Method D 2435 can be used to determine the compressibility of saturated or unsaturated fly ash samples. Fly ash is relatively permeable and consolidates rapidly, therefore it typically is not a design concern. Because of the non-cohesive nature of fly ash, extra care in sample handling is needed.

6.3.8 *Plasticity Index*—Test Method D 4318 is a commonly used test for classifying and comparing fine-grained soils. Because fly ash is nonplastic and is vitrified, correlations developed for cohesive soils with clay particles may not be applicable to ash. The plastic limit determination may be performed to ensure that the fly ash is nonplastic.

6.3.9 *Swelling*—Test Methods D 3877 can be used to determine the swelling potential of cementitious fly ash. The procedure should be modified to extend the wetting and drying cycles to a frequency determined by a qualified design engineer.

6.4 *Chemical Characteristics*—Chemical analyses are routinely conducted by many coal ash producers as a means of determining material variation. The results of these analyses should be communicated to users of this material by means of a Material Safety Data Sheet (MSDS) or some similar communication. For the structural fill designer these results provide information on characteristics that may need to be considered in design, particularly with regard to assessing chemical interaction between fill and other materials or structures. Leachate tests may also be conducted when required by local regulatory agencies.

6.4.1 *Chemical Composition*—Test Methods C 311 is often used to determine the major chemical constituents of fly ash samples.

6.4.2 *pH*—Test Method D 4972, Practice D 5239, or EPA 9045 may be used to determine fly ash pH. In assessing the test results, consideration should be given to the possibility that fly ash and fly ash leachate pH will vary with age, water content, and other conditions.

6.4.3 *Resistivity*—Test Method G 57, a field test, is used to measure fly ash resistivity as an indicator of possible corrosion potential for embedded metals. An alternate laboratory procedure is AASHTO Interim Method of Test T 288. Likely field water contents should be considered in assessing test conditions and results. Field water contents in drained ash fills are likely to be close to the optimum water content for compaction. AASHTO Interim Methods of Test T 289, T 290, and T 291 provide measurements of the pH, water-soluble sulfate ion content and water-soluble chloride ion content of the fly ash that are useful in evaluating corrosion potential. Test Method G 51 is also used to determine the pH of soil for use in corrosion testing.

6.4.4 *Sulfate*—Sulfate content as determined from the fly ash chemical analysis by Test Method C 311, or other method is used in a preliminary assessment of the potential for sulfate attack on concrete. As with corrosivity, likely field water conditions and variations in concentrations with time should be considered.

7. Design Considerations

7.1 *General*—Design involves developing a plan that satisfies the site specific design requirements within the physical and engineering constraints of the fill material and the proposed function of the completed project. The underlying material and fly ash fill must support its own mass and that of the load to be placed on it without excessive settlement, and require no long-term maintenance beyond that typically exercised for the intended use. If applicable, the fly ash must have sufficient shear strength to provide stable slopes. The design process for fly ash is similar to that normally followed for cohesionless natural soil materials. Refs **(19–22)** provide additional information regarding laboratory testing, design, and construction procedures.

7.2 *Design Process*—The design process is an iterative procedure whereby information concerning site and material constraints are balanced against project goals. Information is developed in increasing detail and analyzed to evaluate whether the site development plan is satisfactory. Adjustments to the development plan or material properties are made to accomplish the project goals.

7.2.1 *Conceptual Site Model*—Initially a conceptual site model is developed that identifies specific site characteristics regarding geology, hydrology, and topography. The pertinent material characteristics such as shear strength, load-bearing capability, and other properties regarding compaction, particle (grain) size, hydraulic conductivity, and general chemical properties should be determined for design use. The model should address the changes in fly ash material properties that occur with age, such as strength gain in cementitious fly ashes. Site and material characteristics are determined by experience, literature search, site reconnaissance, field testing and sampling, and laboratory testing.

7.2.2 *Conceptual Design*—Conceptual design involves preparing a plan for site development that meets project goals within the constraints of site and material characteristics and project finances. A general site layout that balances desired final configuration against current topography, material properties and volumes, and site features is prepared. Since the engineering properties (hydraulic conductivity, strength, and compressibility) of fly ash are a function of the degree of compaction, a study must be performed to establish the degree of compaction which will satisfy the project goals. A general assessment of project feasibility is normally conducted as part of conceptual design.

7.2.3 *Detailed Design*—The detailed design involves drainage design for surface water and ground water, planning of site preparation and determination of final cover. Analyses of structural performance are performed. If needed, corrosion protection for buried metal or concrete is specified. Other considerations include control of capillary action, frost heaving, and erosion prevention.

7.2.4 *Other Design Considerations*—Consideration must be given to potential water quality and air quality impacts in accordance with 4.3.2 and 4.3.3, respectively.

7.2.4.1 During the design process it is also appropriate to resolve any questions and approvals needed from local or state environmental agencies. While requirements vary from state to state, a thorough geologic and hydrologic survey of the site are commonly required.

7.2.4.2 The ultimate end use of the site can present special design considerations. For example, fly ash is not an appropriate medium for septic systems. A thicker soil cover may be appropriate depending on the planned end use of the site. Deed restrictions may be warranted in some instances.

7.3 *Site Preparation and Deep Drainage*—It is standard practice to design fly ash structural fills to be well drained because of the sensitivity of the material to the flow of water (that is, piping). Problems such as slope stability, liquefaction, and frost heave that may result from saturation of fly ash are thus avoided. Typically, drainage blankets to provide internal drainage and serve as a capillary barrier are included at the base of fly ash fills. Also, locating fly ash fills in areas where they are not subject to inundation by surface or ground water is normally considered in design.

7.3.1 *Site Preparation*—Site preparation involves developing the site in a suitable condition to facilitate construction of the structural fill. Surface drainage is diverted and controlled. Erosion and sedimentation controls are installed. If needed, wet areas are allowed to drain and dry. Unsuitable materials such as vegetation and topsoil are removed and the subgrade is compacted. Provisions to stockpile any soil needed for final cover are included.

7.3.2 *Site Drainage*—Provisions for positive site drainage are essential if the structural fill is to be reliably maintained in an unsaturated condition. Drainage of seeps and springs encountered during construction should be provided for in design of a site drainage system. A series of perforated pipe drains or aggregate-filled trenches are commonly used for this purpose. These systems are flexible and can be expanded in areal extent as needed to accommodate conditions encountered during construction. Adequate filter protection of drains to ensure long-term, maintenance-free performance should be included. Any provisions needed to control site ground water levels through collection and drainage should be included in the design.

7.3.3 *Drainage Blanket*—A drainage blanket of material coarser than the fly ash used in the fill is commonly used to ensure drainage of the fill. The drainage blanket also serves as a barrier to capillary saturation. Coarser coal ash such as bottom ash often has a suitable particle size range to serve as a drainage blanket for fly ash. Sand, gravel, or other aggregate can also be used depending upon the gradation of these materials. Adequate filter protection such as a geotextile between the fill and drainage blanket must be considered and included to ensure satisfactory long-term performance. The drainage blanket should be designed so that the outlets will remain freely drained. Including outlet pipes with rodent screens is one method that is often satisfactory.

7.4 *Surface Cover and Drainage*—Provisions must be made for controlling erosion of fly ash fills. Due to its fine-grained, non-cohesive nature, non-cementitious fly ash is readily eroded. Unprotected, compacted fly ash is erodible when exposed to surface runoff or high winds. Erosion control is normally accomplished by controlling surface drainage and establishing permanent cover with pavement or soil and vegetation.

7.4.1 *Cover*—Effective cover to control erosion can be either pavement or soil depending upon the final use of the surface. Surface configuration should include provisions for controlled, positive drainage of surface runoff. Minimum slopes to prevent ponding both on surfaces and in drainage ways of approximately 1 to 3 % are desirable so that settlement and minor surface variations can be accommodated.

7.4.2 *Soil Thickness/Vegetation*—The required thickness of soil cover varies and will depend upon site use, climate, and the type of vegetation to be established. The most important consideration is to control wind and water erosion of the surface. On sites where erosion potential is small, 6 in. (150 mm) of cover may provide protection, but 1 ft is probably a practical minimum thickness in most cases. Where erosion potential is greater, or deeper rooted vegetation is planned, or cases where uptake of trace elements and salts from fly ash is a concern, greater thicknesses are warranted. In some cases fly ash/soil blends are used as part of the cover to reduce the need for soil borrow. In these applications, testing of the blend to determine its suitability as a growing medium should be conducted.

7.4.3 *Surface Drainage*—Positive surface drainage is needed to prevent ponding that can lead to erosion problems. Suitable channel linings designed to accommodate storm flows without damage are needed. Slopes on surface areas and in drainage channels should be sufficient to prevent ponding and avoid long-term maintenance problems.

7.5 *Structural Performance*—In order to perform satisfactorily, the fill must support its own mass, that of the loads to be placed on it, and have acceptable settlement. Each of these aspects is analyzed as part of the design process.

7.5.1 *Slope Stability*—Embankment slopes should be stable and able to stand without slumping or sliding. Stability analyses should consider static, dynamic and seismic loadings, and seepage forces, as appropriate. Desired factors of safety typically range from 1.2 to 1.5, depending upon the possibility of occurrence and impact on embankment performance. Stability of exterior slopes, foundation soils and embankment combined, and cover soils should be analyzed.

7.5.2 *Bearing Capacity*—Structures located on or within the fill should be stable and function without excessive settlement or tilting. The bearing capacity of foundations supported by the fill and underlying materials should be analyzed. The ability of the fill to support slabs and pavements to be located on the fill surface should be assessed.

7.5.3 *Settlement*—Settlement due to compression of the fill and the underlying materials should be considered in design. Settlement may adversely affect project performance if not considered in design. Alternately, consideration of settlement magnitude and duration is commonly compensated for in the design process without difficulty.

7.6 *Compaction*—Proper and uniform compaction (including control of molding water content) of fly ash placed in the structural fill increases the strength of the material, reduces the compressibility, and produces a relatively uniform structural fill. Fly ash is readily spread and compacted by conventional construction equipment; vibratory compactors operated at or near resonant frequency are particularly effective. Because it is fine-grained, fly ash exhibits compaction behavior under static compaction similar to natural soils in that its compaction is sensitive to molding water content. Most fly ashes have well-defined compaction relationships, that is, for a given static compactive energy, there exists an optimum water content at which compaction of the fly ash will achieve the maximum dry unit weight. Attempting to compact fly ash above the optimum water content results in displacement of the fly ash and limited densification is attained. Using static compaction, the compaction of fly ash with water contents below the optimum water content, requires more compactive effort to achieve desired results. However, the compaction of fly ash is not especially sensitive to variations in water content when using vibratory compactors operated at the resonant frequency. Thus, fly ash that is several percent below the optimum water content can be readily compacted using vibratory compactors operated at the resonant frequency.

7.6.1 *Placement of Fly Ash*—Since strength in fly ash is derived from internal friction, and this value is dependent upon relative compaction/unit weight of the fly ash, it is necessary to spread the fly ash uniformly and compact it in loose layers not exceeding 1 ft (300 mm) in thickness.

7.6.2 *Degree of Compaction*—A typical requirement is that the fill be compacted to 95 to 100 % of the maximum dry unit weight, in accordance with Test Method D 698, or 90 to 95 % of the maximum dry unit weight in accordance with Test Methods D 1557. Similar requirements are usually applied for the subgrade. In contrast to some soils, variation in absolute values of unit weights determined by the range in percentage of maximum dry unit weights previously specified for the two methods are usually relatively small with fly ash. Therefore either method is suitable. However, the desired performance of the site in terms of safe slopes and adequate performance of foundations, structures, roadways, and so forth, will dictate the degree of compaction needed. Compaction and water content specifications may dictate either the construction method to be used or the performance standard to be attained.

7.6.3 *Method Specifications*—Method specifications specify the type of compaction equipment, the fill material placement methods, and the number of equipment passes to be used in compaction. Method specifications are based on the results of field compaction tests on trial test strips. The test strips are normally conducted at the construction site using the equipment proposed for use and materials from the borrow source or sources that will supply fill material for the project. Method specifications have the advantage of providing continuous quality control by monitoring the ongoing construction activities. If the material source changes or the material itself changes during construction, then the field testing should be repeated on the new material. Method specifications may also be useful for situations where variations in material properties make determination of the appropriate compaction curve difficult.

7.6.4 *Performance Specifications*—For highway embankments performance specifications are commonly used. A typical requirement is that the fill be compacted to 95 to 100 % of the maximum dry unit weight, in accordance with Test Method D 698 or 90 to 95 % when Test Methods D 1557 is used, and at the molding water contents that do not exceed the optimum water content plus a given percentage and that prevent dusting during placement and compaction. When using static-type compaction, an allowable range of water contents is also usually specified so that the material will be in the range where the required unit weight can be readily achieved. Fly ash has a tendency to be displaced under the mass of the compactor when placed above the optimum water content. Specifications requiring placement over a range of water content less than the optimum water content will control this phenomenon. Experience has shown that vibratory compactors operating at the resonant frequency can achieve the required degree of compaction in a minimum of passes over a wide range of water contents, but not excessively wet of the optimum water content.

7.6.5 *Dust Control*—Dusting does not occur during placement and compaction of fly ash when the molding water content of the ash is sufficient to achieve the desired degree of compaction. Ash surfaces exposed to the sun and wind can dry out and become susceptible to dusting. Dusting can be controlled by wetting the ash, applying a dust suppressant, or by placing the final soil cover.

7.7 *Protection of Embedded Materials*—When materials are to be embedded in the structural fill, it is prudent during design to assess whether any deleterious reactions are likely to occur. Specifically, the potential for corrosion of pipes, conduits, and other metal structures should be evaluated. Concrete structures such as culverts, footings, and retaining walls should be evaluated for sulfate attack.

7.7.1 *Corrosion Protection*—Low resistivity is commonly used as an indicator of the corrosion potential of soil or aggregates. Field tests with fly ash have shown that additional contributing factors are high or low pH, high sulfate and chlorides, and partially saturated field moisture conditions. It is appropriate to check all of these factors and consider the lifetime and sensitivity of the embedded material. Large, relatively thick materials like sheet piling are less sensitive than thin-walled piping. For sensitive structures, bitumen or polymer coatings or cathodic protection can be used. Appropriate test methods are described in 6.4.3. The standards used by the local state transportation agency for evaluating corrosion potential of soil fill may be used as a reference.

7.7.2 *Sulfate Attack on Concrete*—Sulfate attack on concrete in fly ash fills has received attention because of the sulfate content in some fly ash. The sulfate exposure is considered severe when the water soluble sulfate in soil (or ash) exceeds 0.20 % by weight, or when sulfate in water exceeds 1500 ppm. As with corrosion, other factors such as moisture will be contributing factors. Also as with corrosion, there is a need to assess sensitivity and lifetime of the structure, and the difficulty of replacement or repair. If sulfate exposure is a concern, the use of sulfate-resistant cements such as those described in Specification C 595 or application of polymer or bituminous coatings will provide appropriate protection.

8. Design Methods

8.1 *General*—The underlying materials and the fly ash fill must support its own mass and the loads to be placed on it without excessive settlement, and require no long-term maintenance beyond that typically exercised for the intended use. In addition, settlement due to the consolidation of the soils which lie beneath the fill must be evaluated and maintained within tolerable limits considering the intended use of the site. The process of analyzing these conditions for fly ash is similar to that normally followed for conventional natural soil materials. The procedure entails developing an analytical model of the fill and underlying soils, the relevant site conditions, and determining whether expected physical behavior is within allowable limits. The moisture testing required and the design methods to be used should be determined by a qualified engineer experienced in designing fly ash structural fills. All design work should be performed in accordance with established engineering practices and in accordance with applicable laws and regulations.

8.2 *Slope Stability*—Analysis of structural fill slopes should consider possible failure of the fly ash fill as well as failure of the foundation soils resulting from the load of the fill.

8.2.1 *Seepage and Drainage*—Consideration of high water tables, seepage forces, seismic loadings, and excess pore pressures in foundation soils should be considered, as appropriate. Adequacy of drainage provisions to maintain the fill in a drained condition should be considered.

8.2.2 *Material Properties*—Material properties for the fly ash should be as determined by laboratory testing. Characterization of site materials and conditions should be in accordance with Guide D 420 with sampling, laboratory, and field testing conducted as needed to characterize conditions and develop a site model.

8.2.3 *Stability Analyses*—Stability analyses are typically conducted for circular failure surfaces using the friction circle method that is conservative for most cases. For situations where noncircular failure surfaces are to be analyzed, complex conditions are to be assessed, or more precise estimates are required, other procedures may be used.

8.3 *Settlement*—Settlement analyses should consider compression of the fill resulting from foundations and other loads placed on the structural fill as well as compression of the foundation soils beneath the fill due to the combined mass of the fill and the superimposed loads. Conventional methods of analyses are used as with natural soils.

8.4 *Bearing Capacity*—The ability of the fill to support structures bearing on or within the fill can be calculated by conventional procedures used for natural soils.

8.4.1 *Footings*—Ultimate bearing capacity analysis is appropriate for footings bearing on compacted fly ash structural fills. The analyses is simplified by the drained, noncohesive nature of the fill (except for cementitious fly ashes). The relatively low unit weight of fly ash as compared to natural soils should be considered in the analyses. Footings that are wider than the thickness of the fill below the footing or that are located near the edge of slopes are cases that require special consideration.

8.4.2 *Slabs and Pavements*—The ability of the fill to support slabs and pavements to be located on the fill surface can be assessed by standard pavement design procedures and by determining the modulus of subgrade reaction by Test Methods D 1195 or D 1196, or bearing ratio by Test Methods D 1883 or D 4429, as appropriate.

8.5 *Lateral Earth Pressure*—Lateral earth pressure is the force that a fly ash fill will exert on retaining walls and similar structures. Conventional methods of analysis can be used for fly ash considering that the material is cohesionless and has a lower unit weight than many natural soils. For structures that are fixed and unable to yield, earth pressure at rest coefficients of 0.5 are typically used in estimating loads. For most yielding retaining walls, active earth pressures are determined by Rankine's method. Coulomb's method is generally used for walls over 20 ft (6.1 m) in height.

9. Construction

9.1 *General*—Construction procedures for fly ash structural fills are similar to conventional earthwork operations. Routine methods employed with soil fills to control dusting, erosion, and sedimentation are similarly required.

9.2 *Weather Restrictions*—Construction should be suspended during severe weather conditions. Operations may proceed during moderately wet periods by reducing the amount of water added at the plant or job site to compensate for precipitation. Dry fly ash can also be disked into excessively wet fly ash to reduce the water content to an acceptable level. Because fly ash obtained directly from silos or hoppers dissipates heat slowly, it may be placed during cold weather. If frost penetrates the surface a few inches, it can be removed from the surface or recompacted upon thawing and drying.

9.2.1 *Dust Control*—When exposed to the elements and allowed to dry out, fly ash surfaces are quite susceptible to produce dust. Dust control measures routinely used on earthwork projects are effective in minimizing airborne particulate at fly ash fill sites. Typical controls include hauling fly ash in pneumatic tankers or covered trucks, moisture-conditioning of the fly ash, wetting or covering of exposed fly ash surfaces, chemically treating fly ash surfaces and paving, wetting, and covering of high-traffic haul roads with coarse materials.

9.2.2 *Erosion Control*—Sedimentation and erosion control measures developed in accordance with state and local requirements are usually adequate.

9.3 *Fly Ash Source and Delivery*—Fly ash is typically supplied from preapproved sources containing no extraneous or deleterious material. Non-cementitious fly ash is usually conditioned with water at the plant and hauled in covered dump trucks with tightly sealed tailgates. Cementitious fly ash is typically hauled in pneumatic tank trucks. Care should be taken to not overfill the trucks so that spillage does not occur. Adequate measures must be taken to ensure proper water content when using fly ash that has been stored in landfills, ponds, and lagoons. Cementitious fly ash may be hauled in pneumatic tanker trucks and conditioned with water at the project site or may be partially conditioned and hauled in covered dump trucks to the project site. Trucks should be spray-cleaned with water at the plant to reduce spillage and dust during transport. Provisions should be made for cleaning of public roads in the event spillage does occur.

9.4 *On-site Storage*—Limit on-site storage of fly ash to the minimum quantity required to maintain the construction schedule. For stockpiles, provide sedimentation and erosion controls in accordance with state and local requirements. Cementitious fly ash that is not partially conditioned should be stored dry in pneumatic tank trucks or in suitably protected storage silos. Precautions normally taken for bulk storage of cement and lime may be required.

9.5 *Site Preparation*—The base of the fill should be stripped of vegetation and organic soils. The subgrade should be compacted to the desired dry unit weight and underdrains installed, when required.

9.6 *Fly Ash Placement and Compaction*—Place fly ash in uniform lifts no greater than 12 in. thick. Typically a fly ash fill is compacted with a vibratory or pneumatic-tired roller. Fill should not be placed on saturated or frozen material. If water must be added to obtain optimum water content condition, allow adequate time for the entire lift to equilibrate yet compact before the surface dries out. Water should be sprayed uniformly.

9.7 *Cover*—Structural fill slopes should be covered with soil and revegetated as soon as practicable following the fill placement operations. Top surfaces should also be covered promptly to reduce infiltration of precipitation and runoff into the fill and to minimize surface erosion.

9.8 *Quality Control*—Quality control programs for fly ash structural fills are similar to quality control programs for earthwork projects. These programs typically include visual observation of fly ash placement operations, supplemented with laboratory and field testing to confirm that the structural fill is constructed as designed. The testing requirements will vary depending on whether a method specification or performance specification is used.

9.8.1 Visual observations are typically made to verify lift thickness, the number of passes of the compactor on each lift, and the behavior of the fly ash under the weight of the compaction equipment. Laboratory compaction tests (Test Methods D 698 or D 1557) are performed to establish baseline data needed to control compaction in the field. Field unit weight and water content tests are conducted regularly on compacted lifts to verify that the required degree of compaction is achieved. Test Methods D 1556, D 2167, or D 2922 may be used to determine the field unit weight. Test Methods D 2216, D 4643, or D 4959 may be used to estimate the water content.

9.8.2 It is prudent to maintain daily job logs documenting site conditions, weather, and work activities. Water content and unit weight tests should be taken as specified by the design engineer and whenever visual observations indicate the desired degree of compaction is possibly not being achieved. As a guide in performance specifications, one test for every 1000 to 2000 cubic yards of fill is suggested. At this rate, changes in ash characteristics due to power plant variability can be observed.

10. Keywords

10.1 coal ash; coal combustion by-products; embankment; fly ash; pollution prevention; resource conservation; structural fill; utilization

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TECHNOLOGY APPLICATIONS

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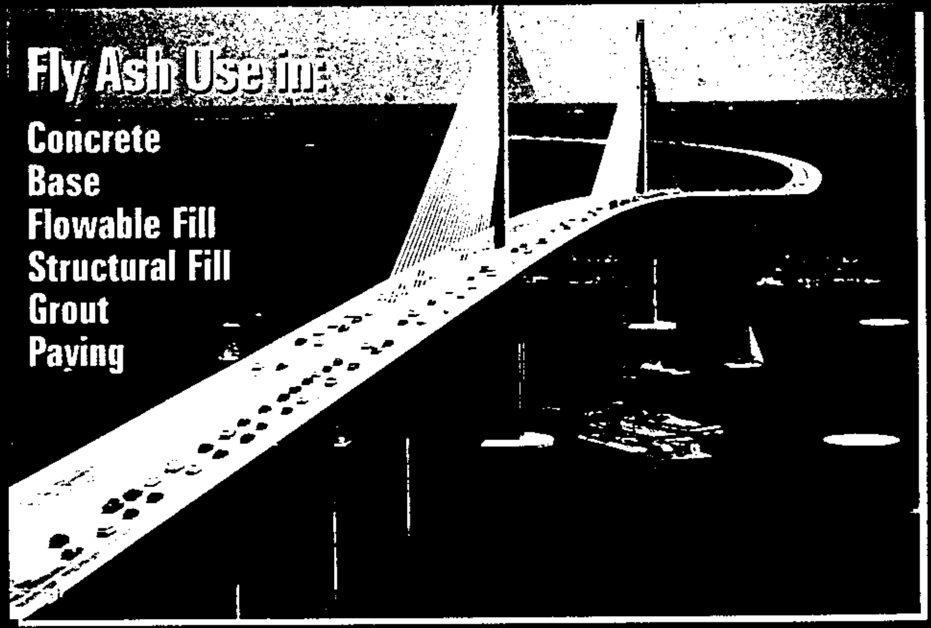
Fly Ash Facts for Highway Engineers



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16. Abstract

Coal fly ash is a coal combustion byproduct (CCB) that has numerous applications as an engineering material; the annual production of CCBs is nearly 82 million metric tons (90 million tons). Since the first edition of *Fly Ash Facts for Highway Engineers* in 1986, substantial information has been accumulated regarding the use of fly ash. The purpose of this document is to provide technical information about engineering applications to potential users of CCBs and to advance the use of CCBs in ways that are technically sound, commercially competitive, and environmentally safe.

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PREFACE

Coal fly ash is a coal combustion byproduct (CCB) that has numerous applications as an engineering material; the annual production of CCBs is nearly 82 million metric tons (90 million tons). Since the first edition of *Fly Ash Facts for Highway Engineers* in 1986, substantial information has been accumulated regarding the use of fly ash. The purpose of this document is to provide technical information about engineering applications to potential users of CCBs and to advance the use of CCBs in ways that are technically sound, commercially competitive, and environmentally safe.

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CONTENTS

CHAPTER 1 1
Fly Ash as an Engineering Material 1
Why Fly Ash? 1
Production 2
Handling 3
Characteristics 3
Quality of Fly Ash 5

CHAPTER 2 9
Frequent Applications 9
Fly Ash in Portland Cement Concrete 9
Fly Ash in Stabilized Road Bases 10
Fly Ash in Flowable Fill Applications 11
Fly Ash in Grouts for Concrete Pavement Subsealing 12
Fly Ash in Fast Track Concrete Pavements 13
Fly Ash in Structural Fills/Embankments 14

CHAPTER 3 15
Use in Portland Cement Concrete 15
Mix Design and Specification Requirements 19
Effects of Material Characteristics on Fly Ash Concrete Quality . . . 20
Fly Ash Physical Properties 20
Other Constituents 22
Construction Practices 23
General Considerations 23
Plant Operations 23
Field Practices 24
Mixture Proportioning Concepts 26
Fly Ash/Portland Cement Concrete 26

CHAPTER 4 29
Use in Stabilized Road Bases 29
Mix Design and Specification Requirements 29
Mix Proportioning 29
Mix Design Evaluation 30

Control of Materials 31
Construction Practices 31
Mixture Proportioning Concepts 35
Lime/Fly Ash/Aggregate Bases 35

CHAPTER 5 37
Use in Flowable Fill Applications 37
General 37
Mix Design and Specification Requirements 39
Typical Mixture Proportioning Concepts for Flowable Fills 45

CHAPTER 6 47
Use in Grouts for Concrete Pavement Subsealing 47
Mix Design and Specification Requirements 48
Stabilization Materials 48
Additives 48
Mix Design 49
Strength 50
Equipment 50
Opening to Traffic 51
Production and Placement 52
Materials Specifications 53

CHAPTER 7 55
Use in Fast Track Concrete Pavement 55
Laboratory Testing 55
Materials Specifications 56
Additives 57

CHAPTER 8 59
Use in Structural Fills/Embankments 59
Specification Requirements 59
General 59
Construction Practices 60

REFERENCES 67

BIBLIOGRAPHY 69

FIGURES

Figure 1. Fossil fuel power plant schematic. 2

Figure 2. Examples of Class C and Class F fly ash. 5

Figure 3. Fly ash (left) and portland cement (right). 7

Figure 4. Strength gain of fly ash concrete. 15

Figure 5. The addition of fly ash to concrete enhances workability even in very stiff mixes. 16

Figure 6. Typical concrete bleed water curves. 17

Figure 7. Permeability. 18

Figure 8. Fly ash concrete improved both the fresh and hardened concrete properties in the decks and piers of Tampa Bay's Sunshine Skyway Bridge. 18

Figure 9. Hydration Reaction. 20

Figure 10. Fly ash concrete for bridge construction. 25

Figure 11. In-place mixing of fly ash-stabilized road base. 30

Figure 12. Spreading fly ash-stabilized road base after central plant mixing. 32

Figure 13. Achieving final grade with a motor grader before final compaction. 33

Figure 14. Flowable fill used as backfill material for a utility trench allows rapid return of traffic to the roadway. 37

Figure 15. Flowable fill eliminates the need for workers to enter the trench to compact. 38

Figure 16. With flowable fill, the width of the trench need not accommodate compaction equipment, resulting in additional savings. 39

Figure 17. Bridge abutment backfill with flowable fill. 42

Figure 18. Bridge replaced by culverts and flowable fill. 44

Figure 19. Fly ash grouts for pavement subsealing. 47

Figure 20. Fast track concrete pavements with fly ash concrete. . . . 55

Figure 21. Highway embankment with fly ash structural fill. 59

Figure 22. Spreading fly ash structural fill. 61

Figure 23. Compaction of fly ash structural fill is crucial, as with any backfill material. 62

TABLES

Table 1. 1993 fly ash production and use. 2

Table 2. 1993 fly ash uses. 3

Table 3. Typical chemical compositions. 4

Table 4. Standard specifications for determining fly ash quality. . . 6

Table 5. High fly ash content mixes—typical proportions. 45

Table 6. Low fly ash content mixes—typical proportions 45

Table 7. Mixture proportioning concepts. 58

Table 8. Combinations required for 95 percent of the standard proctor maximum dry density, AASHTO Method T99-81. 65

CHAPTER 1
Fly Ash as an Engineering Material

WHY FLY ASH?

What is fly ash? Fly ash is the finely divided residue that results from the combustion of pulverized coal and is transported from the combustion chamber by exhaust gases.

Where does it come from? Fly ash is a byproduct of coal-fired electric generating plants. The coal is pulverized and blown into a burning chamber where it immediately ignites to heat the boiler tubes. Heavier ash particles (bottom ash or slag) fall to the bottom of the burning chamber and the lighter ash particles (fly ash) remain suspended in the exhaust gases. Before leaving the stack, these fly ash particles are removed by an electrostatic precipitator, bag house, or other method. See figure 1.

What makes it useful? Fly ash is a pozzolan, meaning it is a siliceous or siliceous and aluminous material that, in the presence of water, will combine with an activator (lime, portland cement or kiln dust) to produce a cementitous material.

What are we doing with it? Currently, approximately 9.53 million metric tons (10.5 million tons) of coal fly ash are used annually for engineering applications. The greatest volumes of ash are used in cement and concrete products, structural fills, and roadbases.

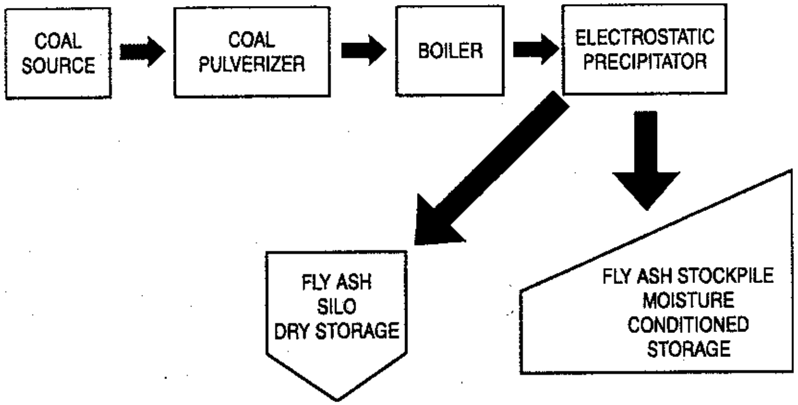

Figure 1. Fossil fuel power plant schematic.

PRODUCTION

Three basic types of burners produce fly ash. Pulverized coal burners are the most widely used. The other two types are stoker fired and cyclone burners.

Table 1. 1993 fly ash production and use.

	Million metric tons	Million short tons	Percent
• Produced	43.50	47.8	100.0
• Used	9.53	10.5	22.0

As shown in table 1, of the 43.5 million metric tons (47.8 million tons) of fly ash produced in 1993, only 9.53 million metric tons (10.5 million tons), or 22 percent of total production, was used. The following is a breakdown of fly ash uses, much of which is used in the transportation industry.

Table 2. 1993 fly ash uses.

	Million metric tons	Million short tons	Percent
Cement and concrete products	6.17	6.8	65%
Roadbase/subbase	.91	1.0	9.5%
Structural fills, embankments	.83	.91	8.7%
Flowable fills	.34	.38	3.6%
Filler in asphalt mixes	.10	.11	1.0%
Grouting	.02	.02	0.2%
Waste Stabilization	.40	.44	4.2%
Other applications	.76	.84	7.8%
	9.53	**10.5**	**100**

HANDLING

Fly ash is most often collected by electrostatic precipitators or bag houses. It is usually handled and stored in silos much like portland cement. The majority of fly ash produced is managed in one of three ways:

- Collected in closed trucks and placed in a monofill storage site.
- Conditioned (by the addition of about 20 percent water), placed and compacted at a monofill storage site.
- Mixed with large quantities of water and sluiced to a storage pond (often with bottom ash).

CHARACTERISTICS

Size and Shape. Fly ash particles are generally spherical and similar in size to portland cement and lime.

Chemistry. Fly ash particles are composed of glass with crystalline matter, carbon, and varying quantities of lime. Fly ash is divided into two classes based on the chemical composition of the ash. Ashes from subbituminous and lignite coals are Class C ashes and may contain more than 20 percent CaO. Ashes from bituminous and anthracite coal are Class F ashes and generally contain less than 10 percent CaO. Typically, Class C ashes contain 1 percent to 3 percent free lime and are reactive with water. Class F ashes generally contain no free lime.

Table 3. Typical chemical compositions.

Compounds	Fly Ash Class		Portland Cement
	Class F	Class C	
SiO_2	54.9	39.9	22.6
Al_2O_3	25.8	16.7	4.3
Fe_2O_3	6.9	5.8	2.4
CaO(Lime)	8.7	24.3	64.4
MgO	1.8	4.6	2.1
SO_3	0.6	3.3	2.3

Color. Fly ash can be tan to gray or black, depending on the source. Tan usually indicates a higher lime content, and gray to black indicates a higher carbon content. Typical samples of the two classes are shown in figure 2.

Figure 2. Examples of Class C and Class F fly ash.

QUALITY OF FLY ASH

What determines fly ash quality? Various aspects of the production process affect fly ash quality. The four most relevant characteristics of fly ash are loss on ignition, fineness, chemical composition, and uniformity. *Specification for Fly Ash in Concrete,* page 8, details these requirements.

Loss on ignition (LOI) is a measurement of unburned carbon (coal) remaining in the ash and is perhaps the single most critical characteristic of fly ash. Higher carbon contents can result in significant air-entrainment problems and can adversely affect the performance of concrete incorporating the ash.

Fineness of a particular fly ash is most closely related to the operating condition of the coal crushers and the grindability of the coal itself. It is a measure of the percent retained on the No. 325 sieve. A coarser gradation can result in a less reactive ash as well as higher carbon contents.

Chemical composition of an ash relates directly to the coal burned. Sources of coal are often blended at the production facility to achieve maximum efficiency from available fuel. Even where sources are not changed, variations in blending can affect ash chemistry, which directly affects its performance.

Uniformity of fly ash characteristics from shipment to shipment is imperative in order to produce a consistently good product. Variations in ash characteristics must be known in advance so mix designs and field procedures can be adjusted as appropriate. Be sure to conduct adequate testing prior to using a particular fly ash in an engineering design.

How can I know I'm getting good quality? The standard specifications used to determine fly ash quality are listed in table 4.

Table 4. Standard specifications for determining fly ash quality.

ACI 229R-94	Controlled Low Strength Materials (CLSM)
ASTM C 311	Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in Portland Cement Concrete.
ASTM C 618 (AASHTO M 295)	Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete.
ASTM C 593	Fly Ash and Other Pozzolans for Use With Lime
ASTM D 5239	Standard Practice for Characterizing Fly Ash for Use in Soil Stabilization
ASTM PS 23-95	Guide for the Use of Coal Combustion Fly Ash in Structural Fills

Methods of ensuring conformance with specifications vary from State to State and source to source. Some States require sealed silo testing and approval before use. Others maintain lists of approved sources and accept project suppliers' certifications of fly ash quality. The degree of quality control necessary depends on one's experience with a particular ash and its specific history of variability. When possible, purchasers prefer source approval with shipment certification to prior testing and approval of each shipment. Costs increase when silos are required for storing the material during the approval process; silo storage should be required only when necessary for acceptable control. Several States have adopted source approval/shipment certification procedures that, with minimal effort, could be adapted to a particular purchaser's needs.

Do I need to know more about this technology to use it confidently? Fly ash can produce a quality product at a competitive cost if appropriate precautions are taken in its use. This publication provides a general overview of fly ash uses from a materials, design, and construction perspective. It will familiarize generalist highway engineers and inspectors with this technology. This publication is designed to assist those individuals who have little or no previous experience using fly ash or experience in a particular application of fly ash.

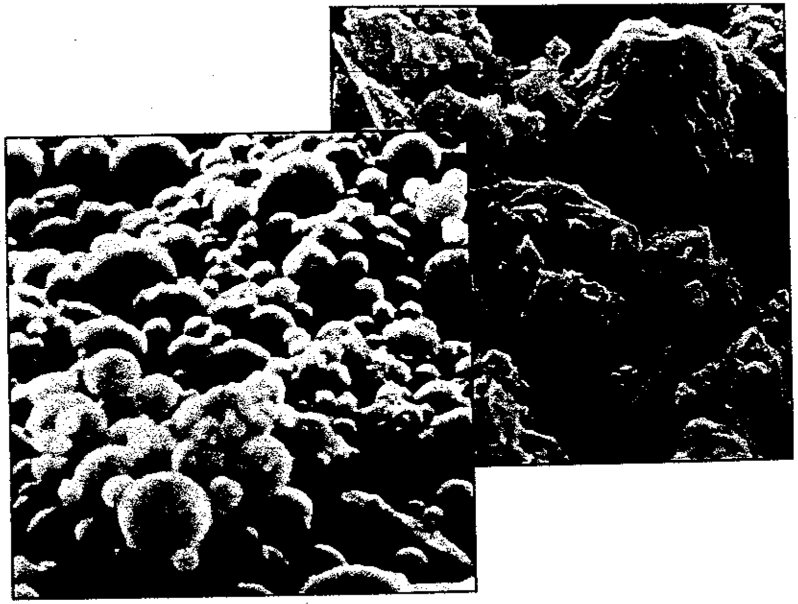

Figure 3. Fly ash (left) and portland cement (right).

SPECIFICATION FOR FLY ASH IN CONCRETE

AASHTO M 295 (ASTM C 618)	Class F & C	
Chemical Requirements		
$SiO_2 + Al_2O_3 + Fe_2O_3$	min%	70[1]
SO_3	max%	5
Moisture content	max%	3
Loss on ignition (LOI)	max%	5[2]
Optional Chemical Requirements		
MgO	max%	5[3]
Available alkalies	max%	1.5[4]
Physical Requirements		
Fineness (+ 325 Mesh)	max%	34
Pozzolanic activity/cement (7 days)	min%	75[5]
Pozzolanic activity/lime	min psi	--[6]
Water requirement	max%	100[7]
Autoclave expansion	max%	0.8
Uniformity requirements:		
Specific gravity variability	max%	5
Fineness variability	max%	5
Optional Physical Requirements		
Multiple factor (LOI x Fineness)		255[8]
Increase in drying shrinkage	max%	.03
Uniformity requirements:		
A.E. Mixture demand air entraining Agent demand	max%	20
Cement/Alkali Reaction:		
Mortar expansion (14 days)	max%	0.020

Notes:
1. Class C requirements are 50 percent
2. ASTM requirements are 6 percent
3. No ASTM requirements
4. Optional requirements per ASTM
5. ASTM requirements are 75 percent of control at 28 days
6. ASTM requirements are 5516 kPa (800 psi) minimum @ 7 days for Class F
7. ASTM requirements are 105% maximum
8. No requirement for Class C

CHAPTER 2
Frequent Applications

FLY ASH IN PORTLAND CEMENT CONCRETE

Overview: Benefits and Cautions

Is fly ash in PCC a new idea? As early as 1914, *Engineering News Record* published research results recognizing that portland cement concrete can benefit from the addition of fly ash. Since then, various organizations have conducted considerable research demonstrating the satisfactory performance of fly ash concrete under diverse conditions.

How does it work? Portland cement contains about 65 percent lime. During the hydration process, some of this lime becomes free and available. When fly ash is present in the free lime mix, it reacts with this cementitious material.

What are the benefits? Research has demonstrated the many benefits of incorporating fly ash into a portland cement concrete mix. It must be emphasized that not all benefits will be realized in every case. Fly ashes and portland cements vary, as do field conditions, but some of the benefits are:

- Significant strength gain.
- Improved workability.
- Reduced bleeding.
- Reduced heat of hydration.
- Reduced permeability.
- Increased resistance to sulfate attack.
- Increased resistance to alkali-silica reactivity.
- Lowered costs.

Some of the cautions that should be observed when using fly ash in concrete are:

- Decreased air entraining ability.
- Decreased early strength.
- Seasonal limitations.

These limitations should not discourage the use of fly ash in concrete. However, they should be considered during design and practice. Evaluate each mix to determine which benefits and cautions apply. Chapter 3 includes a discussion of the benefits and cautions. *Mixture Proportioning Concepts*, page 26, discusses sample mix designs.

FLY ASH IN STABILIZED ROADBASES

Overview: Benefits and Cautions

What is it? Fly ash and lime* can be combined with aggregate to produce a good quality stabilized roadbase. These roadbases are often referred to as pozzolanic-stabilized mixtures (PSMs). Typical fly ash contents may vary from 12 to 14 percent with corresponding lime contents of 3 to 5 percent. Portland cement may also be used in lieu of lime to increase early age strengths. The resulting material is produced, placed, and even looks like cement-stabilized aggregate base.

PSM bases have many advantages over other base materials. Some of the benefits are:

- Use of locally available materials.
- Provides a strong, durable mixture.
- Lowered costs.
- Autogenous healing.
- Increased energy efficiency.
- Suitable for using recycled base materials.
- Can be placed with conventional equipment.

Some of the cautions when using a PSM are:

- Seasonal limitations.
- Traffic loading before complete curing.
- Proper sealing and protection with asphalt or other surface treatment.

**Other materials containing lime, such as portland cement and kiln dust, may also be used but may require testing or certification.*

Chapter 4 provides a basic understanding of PSM base design and construction, and mixture proportioning concepts are detailed on page 45. Additional information can also be obtained from the American Coal Ash Association's *Flexible Pavement Manual*, December 1991. See the reference list, page 67.

FLY ASH IN FLOWABLE FILL APPLICATIONS

Overview: Benefits and Cautions

What is flowable fill? Flowable fill is a mixture of coal fly ash, water, and portland cement that flows like a liquid, sets up like a solid, is self-leveling, and requires no compaction or vibration to achieve maximum density. In addition to these benefits, a properly designed flowable fill may be excavated later. For some mixes, an optional filler material, such as sand, bottom ash, or quarry fines, is added. Flowable fill is also referred to as controlled low-strength material, flowable mortar, or controlled density fill. It is designed to function in the place of conventional backfill materials such as soil, sand, or gravel and to alleviate problems and restrictions generally associated with the placement of these materials.

Benefits of using flowable fill include:

- Allows placement in any weather—even under freezing conditions.
- Achieves 100 percent density with no compactive effort.
- Fills around and under structures that would be inaccessible to conventional fill placement techniques.
- Increases soil-bearing capacities.
- Prevents post-fill settlement problems.
- Increases the speed and ease of backfilling operations.
- Decreases the variability in the density of the backfilled materials.
- Improves safety at the job site and reduces labor costs because no workers are required in the trench.

- Decreases excavation costs because no space is required for compaction equipment and less material needs to be removed
- Available from practically all ready mixed concrete producers who use fly ash in their operations.
- Allows easy excavation later when properly designed.

Cautions to observe when using flowable fill include:

- Anchor lighter weight pipes to prevent floating.
- Needs confinement before initial set of the material.

Chapter 5 includes a detailed discussion of flowable fill applications. Typical mix designs are presented in tables 5 and 6, *Typical Mixture Proportioning Concepts for Flowable Fills*, on page 45.

FLY ASH IN GROUTS FOR CONCRETE PAVEMENT SUBSEALING

Overview: Benefits and Cautions

What are grouts? Grouts are proportioned with fly ash and other materials to fill voids under the pavement system without raising the slabs (subsealing) and to raise and support concrete pavements at specified grade tolerances by drilling and injecting the grout under specified areas of the pavement.

The benefits of using fly ash grouts are:

- Can be used to correct undermining without removing overlying pavement.
- Can be accomplished quickly with minimum disturbance to traffic.
- Can develop high ultimate strength.

Cautions to observe when using fly ash grouts are:

- May require curing period before extremely heavy loading because of low early strength.
- Requires confinement for grout mixture under pavement.

In Chapter 6, the section on *Mix Design*, page 49, presents more information on this topic.

FLY ASH IN FAST TRACK CONCRETE PAVEMENTS

Overview: Benefits and Cautions

Where can fast track pavements be used and what are the benefits? Increasing public and commercial use of existing airports, roadways, and urban streets has introduced major problems for airport authorities and State and municipal governments. Traditional repair or replacement solutions are aggravated by the ever-increasing traffic volumes and the public's consciousness of traffic interruption. These problems are especially acute in urban areas where congestion is most severe.

Fast track portland cement concrete (PCC) pavement construction can help resolve these problems with the following four benefits:

- Provides high-quality, long-lasting results.
- Short downtime and quick public access for airfield, highway, and municipal pavements.
- Well-suited for reconstruction or resurfacing with minimal traffic interruption.
- Can be incorporated into almost all pavement types including bonded overlays, unbounded overlays, overlays of existing asphalt, new construction, and reconstruction.

A caution is:

- Ensure proper curing time and conditions.

Taking advantage of fast track concrete construction requires minimal changes in traditional mix design procedures, construction procedures, and responsibilities. Chapter 7 provides information about fast track concrete pavement planning and construction and table 7, *Mixture Proportioning Concepts*, page 58, provides guidelines for mix design.

FLY ASH IN STRUCTURAL FILLS/EMBANKMENTS

Overview: Benefits and Cautions

What is a fly ash structural fill/embankment? Fly ash can be used as a borrow material in the construction of fills. When the fly ash is compacted in lifts, a structural fill is constructed that is capable of supporting buildings or other structures. An embankment is constructed when the fly ash is placed to support roads or to impound water. Fly ash has been used in the construction of structural fills/embankments that range from small fills for highway shoulders to large fills for interstate highway alignments.

When used in structural fills and embankments, fly ash offers several advantages over soil and rock:

- Fly ash is cost-effective in many areas because it is available in bulk quantities and reduces the expenditures for the purchase, permits, and operation of a borrow pit.
- Its low unit weight makes it ideal for placement over low bearing strength underlying soils.
- Its relatively high shear strength (compared to its unit weight) makes it ideal for placement under building foundations.
- Its ease of handling and compaction reduce construction time and equipment costs.

Some cautions are:

- Leachability and interaction with groundwater must be tested on a site-specific basis.
- Fly ash requires dust control and erosion prevention measures.

Chapter 8 includes more information, and equipment, lift thickness, and related information is presented in table 8, page 65.

CHAPTER 3
Use in Portland Cement Concrete

Fly ash in concrete contributes to improved performance in numerous ways.

- ***Resists alkali aggregate.*** Many fly ashes react with available alkalies in the concrete, which makes them less available to react with the aggregate.[1,2,3]
- ***Resists sulfate attack.*** Fly ash combines with lime, which makes it less available to react with sulfates. The resulting cementitous material also blocks concrete bleed channels that can hinder further entry of the aggressive soluble sulfates. This combination often improves a concrete's resistance to sulfate attack.
- ***Increases ultimate strength.*** Fly ash concrete gains strength over time. Mixtures designed to produce equivalent strength at early ages (fewer than 90 days) will ultimately exceed the strength of conventional portland cement concrete mixes. (See figure 4.)

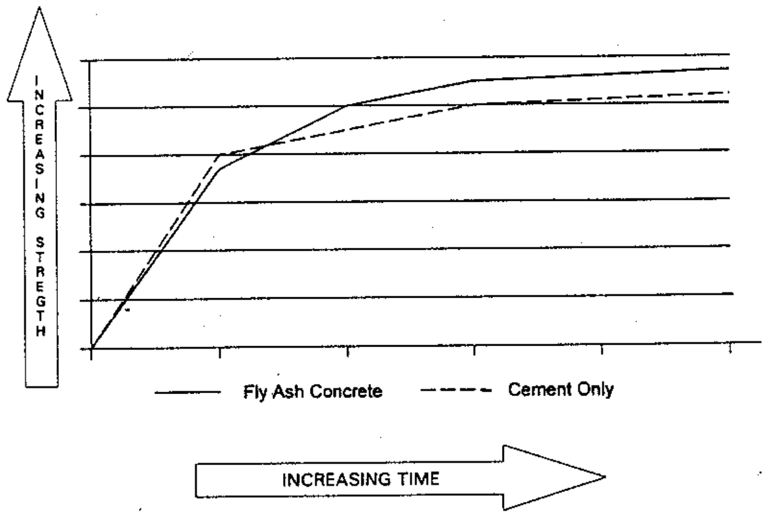

Figure 4. Strength gain of fly ash concrete.

- ***Improved workability.*** The spherical shape and small size of fly ash particles combine to lubricate the mix. (See figure 5.)

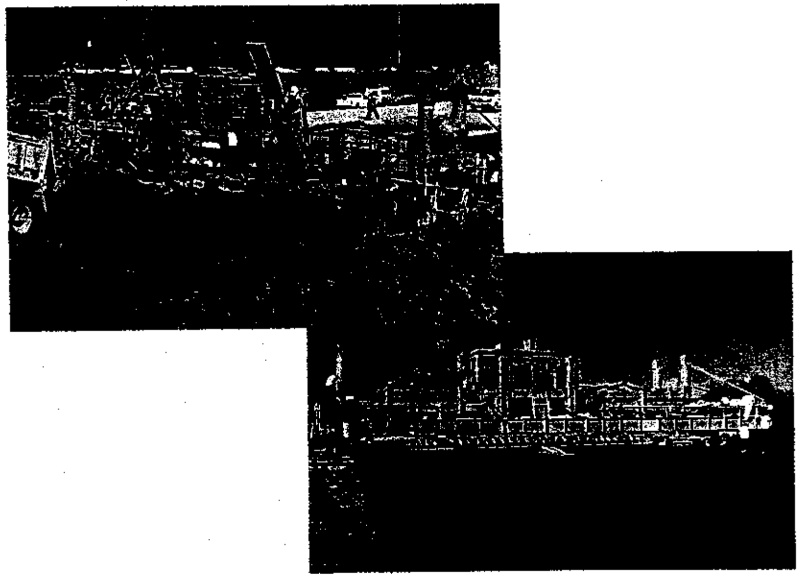

Figure 5. The addition of fly ash to concrete enhances workability even in very stiff mixes.

- ***Reduced bleeding.*** The improved workability leads to lower water requirements, which results in less bleeding and consequently more durable surfaces. (See figure 6.)

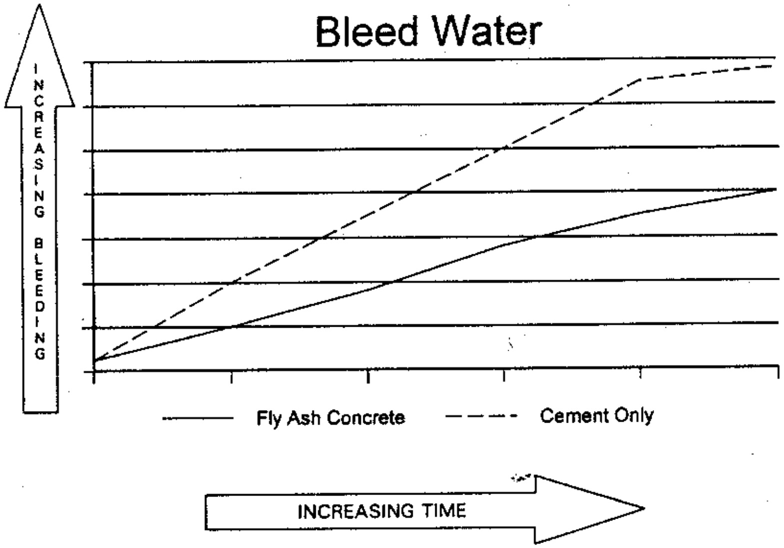

Figure 6. Typical concrete bleed water curves.

- ***Reduced heat of hydration.*** Fly ash reaction generates heat more slowly than the faster reacting portland cement. Some researchers claim that substitution also can slow the hydration of portland cement itself. This combination can lessen heat problems in mass concrete placements.

- ***Reduced permeability.*** Fly ash reaction with available lime and alkalies generates additional cementitous compounds that block bleed channels. (See figure 7.)

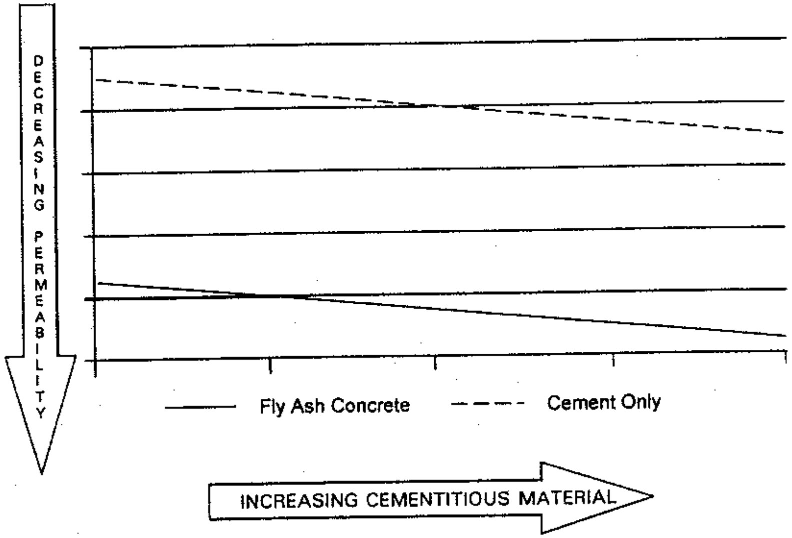

Figure 7. Permeability.

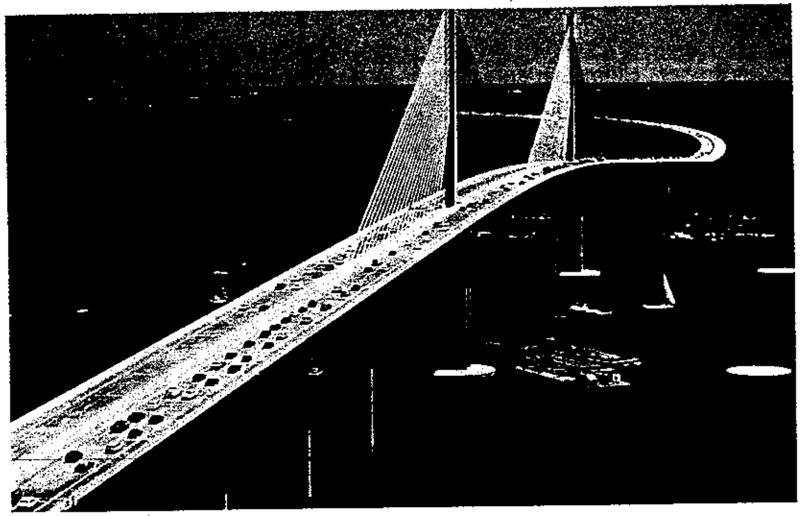

Figure 8. Fly ash concrete improved both the fresh and hardened concrete properties in the decks and piers of Tampa Bay's Sunshine Skyway Bridge.

- ***Lowered costs.*** If the substitution mix design method (discussed in chapter 3) is employed, actual cement costs can be reduced. After considering the cost of incorporating fly ash into a mix, the real savings may be significant.

MIX DESIGN AND SPECIFICATION REQUIREMENTS

Procedures for proportioning fly ash concrete (FAC) mixes necessarily differ slightly from those for conventional PCC. Basic guidelines are contained in the American Concrete Institute (ACI) Recommended Practice 211.1. Highway agencies generally use variations to this procedure, but the basic concepts recommended by ACI are widely acknowledged and accepted. Conceptual procedures for proportioning of fly ash concrete are outlined in *Mixture Proportioning Concepts*, page 26.

There are two basic approaches to developing an FAC mix design. One method removes portland cement and adds fly ash to provide equivalent performance. The second method adds fly ash to a mix design to provide improved performance. Portland cement replacement percentages may vary from 15 percent to 25 percent with some even higher percentages substituted for mass concrete placements. It is recommended that an equivalent or greater weight of fly ash replace the cement removed. Substitution ratios of fly ash to portland cement normally vary from 1:1 to 1.5:1.

A mix design should be evaluated with varying percentages of fly ash. Time versus strength curves can be plotted for each condition. To meet specification requirements, develop curves for various replacement ratios and select the optimum replacement percentage and ratio. This mix design development should be performed using the proposed construction materials.

Cement factors. Because fly ash addition contributes to the total cementitious material available in a mix, the minimum cement factor (portland cement) used in PCC can be effectively reduced for FAC. The ACI acknowledges this contribution and recommends that a water/(cement + pozzolan) ratio be used for FAC in lieu of the conventional water/cement ratio used in PCC.

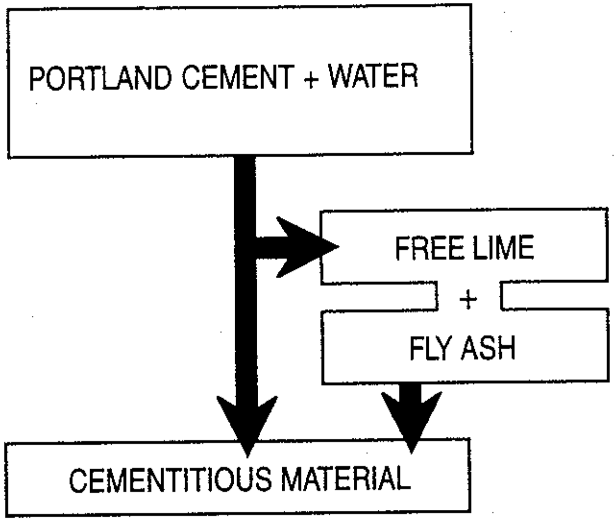

Figure 9. Hydration Reaction

Fly ash particles react with free lime in the cement matrix to produce additional cementitious material and thus, to increase long-term strength.

EFFECTS OF MATERIAL CHARACTERISTICS ON FLY ASH CONCRETE QUALITY

Various characteristics of fly ash and other constituents with which it is used can significantly affect the quality of concrete produced. Those material characteristics of greatest importance and their effects on the product are discussed below.

Fly Ash Physical Properties

Particles. Fly ash consists largely of solid and hollow spherical particles with some irregularly shaped carbon and other particles. The carbon and hollow particles tend to float to the top during the concrete finishing process and may produce dark-colored surface streaks. Larger concentrations of these particles are not desirable.

Fineness. The fineness of fly ash is important because it affects the rate of pozzolanic activity and the workability of the concrete. Specifica-

tions require a minimum of 66 percent passing the No. 325 sieve. Significantly finer ashes (90 to 95 percent + passing No. 325) may increase water requirements and increase the demand for air entraining admixture.

Specific gravity. Although specific gravity does not directly affect concrete quality, it is of definite value in identifying changes in other fly ash characteristics. It should be checked regularly as a quality control measure, and correlated to other characteristics of fly ash that may be fluctuating.

Chemical properties. Silicon dioxide, aluminum oxide, and iron oxide are active components in fly ash. These components react with calcium ions to produce cementitious material. Ashes tend to contribute to concrete strength at a faster rate when these components are mostly present in finer fractions of the ash. The converse is also true.

AASHTO limits magnesium oxide to a maximum of 5 percent to prevent deleterious expansion caused by the formation of magnesium hydroxide.

Sulfur trioxide content is limited to 5 percent as greater amounts have been shown to increase mortar bar expansion. Within specification limits, higher SO_3 contents may in some cases result in higher early concrete strength.

Available alkalies in most ashes are less than the specification limit of 1.5 percent. Concentrations greater than this may adversely affect alkali-aggregate expansion problems. Generally speaking, however, most fly ashes will assist in eliminating potential problems in this area. For more information on alkali-silica reactivity, the Mid-Atlantic Regional Technical Committee has published *Guide to Alkali-Aggregate Reactivity* and *Guide Specifications for Concrete Subject to Alkali-Silica Reactions.*

Loss on ignition (LOI), as stated, is a measurement of unburned carbon remaining in the ash. It can range up to 5 percent per AASHTO and 6 percent per ASTM. This remaining unburned carbon will adsorb air entraining admixtures (AEA) and increase water requirements. Values greater than 3 to 4 percent will probably necessitate significant increases in AEA dosage while lower values may require only minor adjustments. Also, some of the carbon in fly ash may be encapsulated in glass or otherwise be less active and therefore not affect the mix. Variations in this characteristic can contribute to fluctuations in air content and call for more careful field monitoring of entrained air in the concrete.

OTHER CONSTITUENTS

Aggregates. Conduct appropriate sampling and testing to ensure the aggregate to be used in mix design development is of good quality and accurately represents materials that will be used on the project. Some aggregates of marginal quality have been observed to adversely affect the air void matrix in hardened concrete. If durability of an FAC trial batch is below expectations, examine aggregate quality as a possible contributor.

Cement. Fly ash can be used effectively in combination with all types of portland cement, but it is not recommended for routine use with high early strength or pozzolanic cements. Cements vary, as do fly ashes, and not all combinations produce a good concrete. The selected portland cement should be tested and approved on its own merits and also evaluated in combination with the specific fly ash to be used.

Chemical admixtures. Air Entraining Admixtures (AEAs): neutralized vinsol resins are frequently used in FAC and generally produce good results. Unfortunately, they are readily adsorbed by carbon in the ash and thus are quite sensitive to fluctuations in LOI and carbon adsorbency. They will normally produce satisfactory results if the LOI is less than about 4 percent and the ash characteristics do not fluctuate.

Increasing use of fly ash has prompted many companies to develop AEAs specifically for use in FAC. Some of these can produce good results, but it is strongly recommended that the AEA selected for use be evaluated on its own merits. The size, distribution, and durability of bubbles produced, along with the gross amount of air entrained, significantly affect concrete durability. All of these parameters should be evaluated whenever possible because changes in other aspects of FAC mix design can inhibit the effectiveness of AEA.

Retarders. Adding fly ash should not appreciably alter the effectiveness of an otherwise acceptable retarder. However, fly ash in the mix usually delays the time of set and may reduce the need for retarder. In many cases, retarder dosage should be reduced or eliminated to avoid unacceptable delays in concrete set time.

Water reducers. Fly ash concrete normally requires less water, but it can be further improved with the use of water-reducing admixtures. The effectiveness of these admixtures may vary with the addition of fly ash. It is recommended that normal water-reducing admixtures be used in lieu of the retarding types unless it is specifically determined that a retarder is needed.

CONSTRUCTION PRACTICES

General Considerations

The effects to construction practices of using FAC in lieu of conventional PCC depend on the specific characteristics of the mix design being used. FAC mix designs can be developed that will perform essentially the same as PCC mix designs with only minor detectable differences in handling and finishing. When mixing and placing any FAC, some minor changes in field operation may be desirable. The following general rules-of-thumb will be useful.

Plant Operations

Fly ash requires a separate watertight, sealed silo and holding bin. Because the volume of fly ash used is usually significantly less than the volume of portland cement required, it might be cost-effective to store the fly ash in a tanker truck or other container in lieu of a second silo. Take care to clearly mark the loading pipe for fly ash to guard against confusion when deliveries are made.

If a separate holding bin cannot be provided economically, it may be possible to divide the portland cement holding bin. However, use a double-walled divider to ensure there are no small holes. Fly ash particles will flow through even the smallest hole and over time make it much larger.

Fly ash should be weighed on top of the cement. It is not normally good practice to place it into the weigh bin first because it can leak through openings that will hold portland cement.

Take care to keep concrete mixing, agitation time, and conditions as uniform as possible from delivery to delivery. A worn mixer, a little water in a truck, or a driver stopping for a soft drink are examples of seemingly small variables whose effects to the mix could be magnified with the use of fly ash.

Field Practices

Beginning with the first concrete delivery to the job site, check every load for entrained air until project personnel are confident a good consistent air content is being obtained. After that, regular and closely spaced checks should continue to ensure consistency.

Place the concrete as quickly as possible to reduce air loss in the mix during agitation. FAC mix handling characteristics allow it to be placed easily. The need for vibration during placement should be minimal. Definitely avoid excessive vibration because it will lower the in-place air content of the concrete. Adjust automated equipment to ensure that only the minimum vibration necessary to properly place the concrete is provided.

FAC has more cement paste and less bleed water than conventional PCC, thus the surface will be a bit more sticky during the finishing process.

Finishers might be frustrated by the seemingly dry sticky surface, but they should be cautioned against overworking. The unnecessary surface manipulation results in a loss of air in the exposed area of the concrete, which increases the potential for scaling.

The slower strength development of FAC might require that the concrete retain moisture for a longer period of time. Proper application of curing compound will normally retain moisture as long as economically feasible. Other curing methods are certainly acceptable as long as the specified acceptance strength can be achieved.

The improved workability of FAC is likely to result in an overall easier placement. Many contractors report improved smoothness of FAC pavements over those constructed with conventional PCC.

Figure 10. Fly ash concrete for bridge construction.

Has the solution to all our concrete problems finally arrived? If the answer was *yes*, this publication probably wouldn't be needed. Fly ash is simply another material that can be used in the design of a quality concrete mix.

What advice do you have for the first-time user? Even with the benefits listed, the potential effects of fly ash in concrete aren't all wonderful. The user should pay close attention to the following guidelines:

- ***Mix design evaluation.*** Evaluate the performance of proposed mix designs before construction. Good quality constituents do not always produce a mix that will perform as desired.
- ***Air content problems.*** The fineness of fly ash makes it naturally more difficult to develop and hold entrained air. Remaining carbon in the ash also adsorbs some of the AEA. Higher carbon ashes naturally require higher AEA contents. Longer mixing times or other variations from truck to truck can result in larger than normal fluctuations in air content. Testing requirements must ensure that the fly ash used maintains a uniform carbon content (LOI) to mitigate

unacceptable fluctuations in entrained air. Also pay careful attention to air content at the point of placement to ensure against low air content and the problems that can result.

- ***Lower early strength.*** The substitution mix design method will result in lower strengths at early ages. Mix design should consider form removal sequence and anticipated early loading. Lower early strengths can be overcome by using appropriate admixtures or other adjustments to the mix design.
- ***Seasonal limitations.*** Construction scheduling should allow time for FAC to gain adequate density and strength to resist de-icing applications and freeze-thaw cycling prior to the winter months. Strength gain of FAC is minimal during the colder months. Although pozzolanic reactions are significantly diminished below 4.4 °C (40 °F), strength gain may continue at a slower rate resulting from continued cement hydration.

MIXTURE PROPORTIONING CONCEPTS

Fly Ash/Portland Cement Concrete

Note: This procedure presents basic concepts only and is not intended to serve as a complete guide to mixture proportioning of fly ash concrete.

Given: The following target values should be identified prior to proportioning the mix.

- Strength (at designated ages).
- Aggregate size.
- Target water/cement plus pozzolan (w/c+p) ratio.
- Air content.
- Slump.

This publication discusses considerations in selecting these values.

Step 1. Estimate water content.

With the aggregate size and target slump, enter the appropriate table of ACI 211.1 and determine the approximate water required per cubic meter (cubic yard). When fly ash is to be used, this estimated water requirement may be reduced 5 to 10 percent for the initial trial batch.

Step 2. Estimate fly ash and portland cement requirements.

The target w/c+p ratio and the estimated water content in step 1 are used to compute the total cementitious material required.

With the percent of total cementitious material represented as fly ash already selected, we can now compute the actual weights of fly ash and cement.

Step 3. Estimate coarse aggregate content.

The appropriate table in ACI 211.1 provides volumes of dry-rodded coarse aggregate. With the coarse aggregate size and the fineness modulus of the sand, a volume of course aggregate per cubic meter (cubic foot) of concrete can be selected. This volume is then multiplied by the dry-rodded unit weight of the aggregate to obtain the coarse aggregate weight per cubic meter (cubic foot) of concrete.

Step 4. Estimate fine aggregate content.

Estimate fine aggregate requirements by subtracting the total estimated weight of other constituents from the estimated weight of the fresh concrete on a cubic meter (cubic yard) basis. The appropriate table of ACI 211.1 provides first estimates of concrete weight and can be adjusted to meet mix parameters.

Step 5. Adjust trial batch.

Trial batches should be prepared and tested in accordance with ASTM C 192 or full-sized field batches. They should be checked for unit weight and yield (ASTM C 138, C 173, or C 231). They should also be monitored for workability and finishing properties. Make appropriate adjustments and prepare new trial batches. Carefully evaluate concrete from the final mix design before construction to ensure its field performance will be as desired.

CHAPTER 4
Use in Stabilized Road Bases

MIX DESIGN AND SPECIFICATION REQUIREMENTS

Mix Proportioning

When a decision is made to use lime/fly ash/aggregate [pozzolanic-stabilized mixture (PSM)] roadbase, a mixture design must be developed that will:

- Possess adequate strength and durability for its designated use.
- Be easily placed and compacted.
- Be economical.

Quality mixtures have been produced with lime contents ranging from 2 to 8 percent. Fly ash contents may range from 8 to 15 percent. Typical proportions range from 3 to 4 percent lime and 10 to 15 percent fly ash. When conditions warrant, 0.5 to 1.5 percent of Type 1 portland cement can be used to accelerate initial strength gain. More information is presented in the section on *Mixture Proportioning Concepts*, page 35.

Strength development of a PSM is highly dependent on curing time and temperature. A specified minimum curing time as a function of temperature can be designated using the degree-day concept. In this approach the curing degree days necessary is the product of days cured and the curing temperature in excess of 4.4 °C (40 °F).

Evaluate various curing times and temperatures to assess the curing degree-days required to produce the specified strength. More often, minimum curing times are specified along with an allowable curing temperature range that will produce the required strength. Target strengths for mix design development should allow for the fact that PSM bases will continue to develop notable strength after completion of the initial curing period. Higher specified early strengths can result in a PSM base exhibiting future characteristics more like those of a rigid pavement.

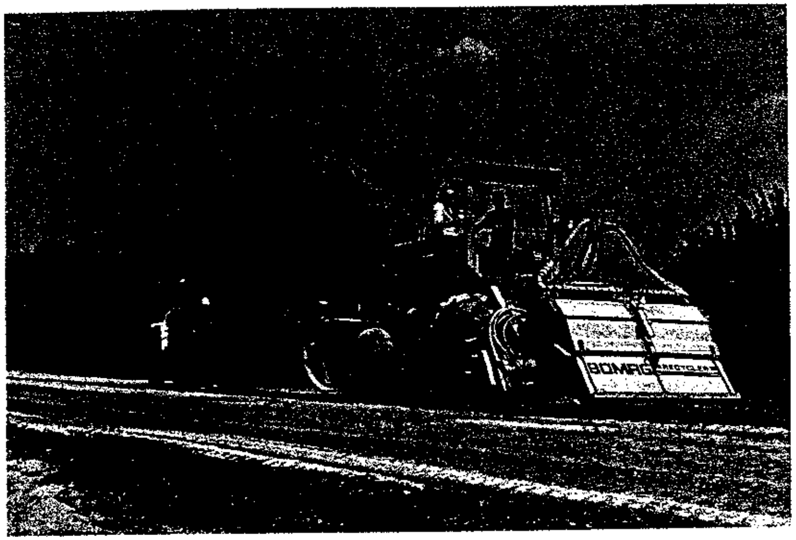

Figure 11. In-place mixing of fly ash-stabilized roadbase.

In designating the required strength, employ the design values used in developing layer thickness. PSM bases were not evaluated at the AASHO Road Test, but subsequent guidance in the selection of layer coefficients has been developed. Agencies should evaluate their own mixes and establish pavement design layer coefficients and corresponding strengths for use in mix design development.[4]

Mix Design Evaluation

Compaction. The density of PSM mixtures significantly affects cured strength. Specimens are normally compacted at moisture content and density as determined by AASHTO T 180.

Strength. Closely controlled curing conditions are important as both time and temperature significantly affect POZZ strength. Use standard proctor-sized specimens; normal curing is at +38 °C (100 °F) for 7 days. As time permits, use other conditions to assess strength development, degree days required, etc. Some agencies are using 14-day curing periods at 22 °C (72 °F).

Durability. It is important to ensure that adequate resistance to freeze-thaw cycling is achieved before the onset of colder months. The vacuum saturation test is normally used per ASTM C 593.

Control of Materials

Lime. Hydrated lime is the most popular form used though quick lime and other products containing lime (kiln dust, etc.) can be used successfully with appropriate precautions. Type 1 portland cement has also been used successfully as a reactant when higher early strength requirements or reactant market conditions dictate. Determine actual lime content from samples using approved titration methods (ASTM D 2901, AASHTO T 232).

Fly ash. Unconditioned (dry) or conditioned (water added) fly ash can be used successfully. Check the reactivity of fly ash with cement in accordance with ASTM C 593 and for comparison and mix design results. Reactivity and fineness are the fly ash characteristics that most directly affect PSM quality.

Aggregates. Aggregates must be sound and resist deterioration from environmental elements. They may include sands, gravels, or crushed stones. Gradation should be such that the final mixture is mechanically stable and highly compactible.

Construction Practices

Blending of materials. Central plant mixing provides the best quality although in-place mixing is successful. Most plants use a continuous pugmill, but central mix concrete plants also work well. When unconditioned (dry) fly ash is used, a silo and surge bin are needed for lime and fly ash. When belt feeding, drop dry fly ash on top of the aggregate to keep it from rolling down the belt during pugmill loading. Conditioned fly ash can be routinely added through an aggregate hopper.

Calibrate plants before beginning an operation and make daily checks to ensure product consistency. Determine and adhere to necessary retention time in the pugmill to achieve proper mixing throughout the operation.

Hauling. The blended mixtures can be hauled to the site in open trucks, but trucks should be covered if there is drying and dusting or long haul distances are required.

Figure 12. Spreading fly ash-stabilized roadbase after central plant mixing.

Spreading. A PSM can be placed with spreader boxes or asphalt laydown machines. Equipment with automated grade control is highly recommended. Layers are normally spread to a thickness of 15 to 30 percent greater than the desired compacted thickness. Maximum lift thickness is 203 to 254 mm (8 to 10 in). Place the second lift on the same day or take appropriate measures to ensure adequate sealing and subsequent bonding of additional lifts.

Compaction. Achieving a high degree of compaction is crucial to the successful performance of PSM roadbases. Final density should be reached as quickly as possible to achieve the highest ultimate strengths. Compacting this noncohesive material with steel-wheel, pneumatic, and vibratory rollers has been successful. The PSM surface should be kept moist throughout compaction. PSM moisture should be on the low side of optimum to achieve the best field compaction. The final surface should be clipped to proper grade with a motor grader before final rolling with a steel-wheeled roller. In clipping, take care not to fill in the low spots because the feathering-in will tend to reduce bonding at that location, thus creating a potential trouble spot.

Figure 13. Achieving final grade with a motor grader before final compaction.

Curing. Compacted layers should be quickly sealed to prevent drying. Apply a prime coat of 0.45 to 0.91 liters per square meter (0.1 to 0.2 gal/yd^2) of cut back or emulsified asphalt to the moist surface within 24 hours of final compaction. Multiple applications of lighter coats tend to produce better penetration and improve adhesion.

Many mixes provide enough mechanical strength to support construction traffic when compaction is completed, but it is recommended that there be minimal early loadings. Opening to traffic should follow at least 7 curing days and only after a suitable riding surface has been placed.

- ***Lower costs.*** The cost of PSM varies notably from area to area but is often less than alternative base materials. Allowing its use can also increase competition.

- ***Autogenous healing.*** Whenever fractured surfaces remain in intimate contact, PSMs have the inherent ability to heal or recement across cracks if moisture is present and unreacted lime and fly ash are available. This phenomenon is known as autogenous healing.

- ***Energy efficient.*** PSMs use a byproduct that requires no energy to produce and, because PSMs need not be heated, it requires less energy to place than asphaltic bases.

What if I can't afford to buy specialized construction equipment? There is no need to with PSMs! Most plants can be readily adapted to produce the pugmilled mix. Depending on the desired control, it can be spread with an asphalt paver or jersey spreader, the latter being the most popular method. A motor grader can be used to spread dumped material, but it is not recommended because of the inability to maintain good control.

When placing PSM bases under relatively thin asphalt pavements, expect transverse cracks to appear within 1 to 3 years. Sawing and sealing of joints is one method used to reduce the adverse effects on appearance and to provide for better future sealing. Joint spacing may vary from 6.1 to 12.2 m (20 to 40 ft) depending on local experience. This approach is still being evaluated.

What advice do you have for the first-time user? PSMs can produce strong durable bases only if attention is paid to the following precautions:

- ***Mix design evaluation.*** Proposed mix designs should be evaluated for performance before construction. Good quality constituents do not always produce a mix that will perform as desired. Many high calcium ashes will require admixture or prior field "conditioning" to produce a mix with acceptable set times.
- ***Seasonal limitations.*** PSMs often require several weeks of warmer weather to develop adequate strength to resist freeze-thaw cycling of the first winter. If late season placements are necessary, add portland cement in lieu of some of the lime to increase early strength.
- ***Curing.*** Moisture must be maintained in the mix to ensure continued strength development. Quickly and properly applied bituminous curing will maintain required moisture as long as economically feasible and should provide satisfactory curing conditions.

MIXTURE PROPORTIONING CONCEPTS

Lime/Fly Ash/Aggregate Bases

Note: This procedure presents basic concepts and is not intended to serve as a complete guide to mixture proportioning.

Step 1. Determine the total quantity of lime activator plus fly ash required to produce the maximum dry density when combined with the proposed project aggregate (optimum fines content). Generally, the recommended fines content is approximately 2 percent above the quantity of matrix material (consisting of fly ash, water, activator and minus No. 4 size aggregate fines) required for maximum dry density.

Step 2. Select the proportion of activator to fly ash. This ratio varies from one constituent source to another. Initial proportions should be based on experience where possible. For best results, prepare trial batches with several ratios and select the most economical one that produces a mix exceeding performance requirements per ASTM C 593. At the recommended fines content determined in step 1, strength development is influenced by adjusting the ratio of the weight of activator to weight of fly ash.

Step 3. Adjust the mix to compensate for construction variability by increasing the designated activator content by about 1/2 percent and the fly ash content by about 1-1/2 percent.

CHAPTER 5
Use in Flowable Fill Applications

GENERAL

Flowable fill has several names, but each is essentially the same material:

- Controlled density fill (CDF).
- Controlled low strength material (CLSM).
- Flowable fly ash.
- High slump fly ash grout.
- Lean concrete slurry.
- Lean mix backfill.
- Unshrinkable fill.

Figure 14. Flowable fill used as backfill material for a utility trench allows rapid return of traffic to the roadway.

Flowable mixtures make up a class of engineering materials having characteristics and uses that overlap those of a broad range of traditional materials including compacted soil, soil-cement, and concrete.[5] Consequently, flowable mixtures are proportioned, mixed, and delivered in a form that resembles a very workable concrete; and they provide for an in-place product that is equivalent to a high-quality compacted soil without the use of compaction equipment and related labor.

Virtually any coal fly ash can be used in flowable fill mixes. The fly ash does not have to meet ASTM C 618 specification requirements as a concrete admixture to be suitable for use in flowable fill mixes. Because low strength development is usually desirable in flowable fill, even fly ash with high LOI or carbon content is suitable. Regardless of the type of handling practices, fly ash for flowable fill can be used in a dry or moisture conditioned form. Fly ash recovered from storage ponds has also been used successfully. Flowable fill mixes using high-calcium fly ash may not require any cement.

Upon comparison, flowable fill materials usually offer an economic advantage over the cost of placing and compacting earthen backfill materials. Depending on the job conditions and costs involved, significant savings are possible. The closer the project location is to the source of the flowable fill, the greater the potential cost savings.

(Photo courtesy of National Ready Mixed Concrete Association)

Figure 15. Flowable fill eliminates the need for workers to enter the trench to compact.

Figure 16. With flowable fill, the width of the trench need not accommodate compaction equipment, resulting in additional savings.

Flowable fill also becomes more economical than conventional earthen backfill if shoring and/or sloping of the trench is necessary for worker safety within the excavated area. (See figure 15.) With flowable fill, workers need not be in the excavation, resulting in cost savings from less excavation and no shoring. (See figure 16.)

MIX DESIGN AND SPECIFICATION REQUIREMENTS

Flowable fills typically contain fly ash and water and may contain portland cement and filler materials in the form of bottom ash, sand or other aggregates. The flowable character of these mixtures derives from the spherical particle shape of fly ash or from a distribution of spherical and irregular particle shapes and sizes in fly ash and sand combinations when mixed with enough water to lubricate the particle surfaces.

Fly ash can be the major ingredient in flowable fills. However, when available sand is more economical, fly ash can be limited to 300 or fewer kilograms per cubic meter (500 or fewer pounds per cubic yard). Water requirements for mixture fluidity will depend on the surface parameters of all solids in the mixture, however, a range of 247.7 to 396.3 liters per cubic meter (50 to 80 gallons per cubic yard) would satisfy most materials combinations. Portland cement is added, typically in quantities from 30 to 59 kilograms per cubic meter (50 to 100 pounds per cubic yard) to provide a weak cementitious matrix. More information on mix design is provided in *Typical Proportioning Concepts for Flowable Fills*, page 45.

The two basic types of flowable fill mixes are high fly ash content and low fly ash content. The high fly ash content mixes typically contain almost all fly ash with a small percentage of portland cement and enough water to make the mix flowable. The low fly ash content mixes contain a high percentage of fine aggregate or filler material (usually sand), a low percentage of fly ash sufficient to help the sand particles flow, a small percentage of portland cement (similar to that used in high fly ash content mixes), and enough water to make the mix flowable.

The American Concrete Institute (ACI) Committee 229 has designated low fly ash content mixes that contain high percentages of fine aggregate as Controlled Low Strength Material (CLSM).

According to the ACI definition, CLSM has an upper compressive strength limit of 8.274 kPa (1200 psi), however, strengths can be designed as low as 344.7 kPa (50 psi). Most flowable fill mixes are designed to achieve a maximum strength of 1034 to 1379 kPa (150 to 200 psi) so as to allow for excavation at a later time.

It is important to remember that flowable fill mixes with an ultimate strength in the 344.7 to 482.7 kPa (50 to 70 psi) range have at least two to three times the bearing capacity of well-compacted earthen backfill material.

Usually, flowable fill mix designs are proportioned based on the percentage of fly, using a dry weight basis. The high fly ash content mixes normally contain 95 percent fly ash and 5 percent portland cement. Because the low fly ash content mixes contain an additional ingredient (sand or filler), there is a much broader range of mix proportions. Some typical mix designs for high and low fly ash content mixes are included in tables 5 and 6, page 45.

The most important physical characteristics of flowable fill mixtures are:

- Strength development.
- Flowability.
- Time of set.
- Bleeding and shrinkage.

These characteristics are discussed in detail on the following pages.

Strength development in flowable fill mixtures is directly related to cement content and water content. Most high fly ash content mixes only require from 3 to 5 percent portland cement by dry weight of the fly ash to develop 28-day compressive strengths in the 344.7 to 1034.3 kPa (50 to 150 psi) range. Long-term strength may gradually increase beyond the 28-day strength. Water content of mix also influences strength development. Water is added to achieve a desired flowability or slump. At a given cement content, increased water content usually results in a slight decrease in compressive strength development over time.

Flowability is basically a function of the water content. The higher the water content, the more flowable the mix. It is usually desirable to make the mix as flowable as practical in order to take advantage of the self-compacting qualities of flowable fill.

Time of set is directly related to the cement content. Typical high fly ash flowable fill mixes containing 5 percent cement achieve a sufficient set to support the weight of an average person in about 3 to 4 hours, depending on the temperature and humidity. Within 24 hours, construction equipment can move across the surface without any apparent damage. Some low fly ash flowable fill mixes containing high calcium fly ash have reportedly set sufficiently to allow street patching within 1 to 2 hours after placement. For most mixes, especially the high fly ash mixes, increasing cement content or decreasing water content or both should reduce the setting time somewhat.

Bleeding and shrinkage are possible in high fly ash flowable fill mixes with relatively high water contents (corresponding to a 254-mm/10-in slump). Evaporation of the bleed water often results in a shrinkage of approximately 10.42 mm/m (1/8-in/ft) of depth of the fill. The shrinkage may occur laterally as well as vertically, but no additional shrinkage or long-term settlement of flowable fill occurs after initial set. Prior to hardening, flowable fill mixes are self-leveling.

Because the flowable fill is commonly obtained from ready mixed concrete producers, quality control of the fill is easily maintained with the materials scales and metering devices already in use at the concrete plant. Delivery is usually by conventional ready mix trucks. Flowable fill can also be pumped or placed by bucket, conveyor, tremie, or hose. It does not usually segregate even if dropped from considerable heights or pumped for long distances.

Applications of flowable fills include but are not limited to backfill for bridge abutments, culverts, and trenches; fill for embankments, bases, and subbases; bedding for slabs and pipes; insulating fill; fill for caissons and piles; and fill for abandoned storage tanks, shafts, and tunnels.

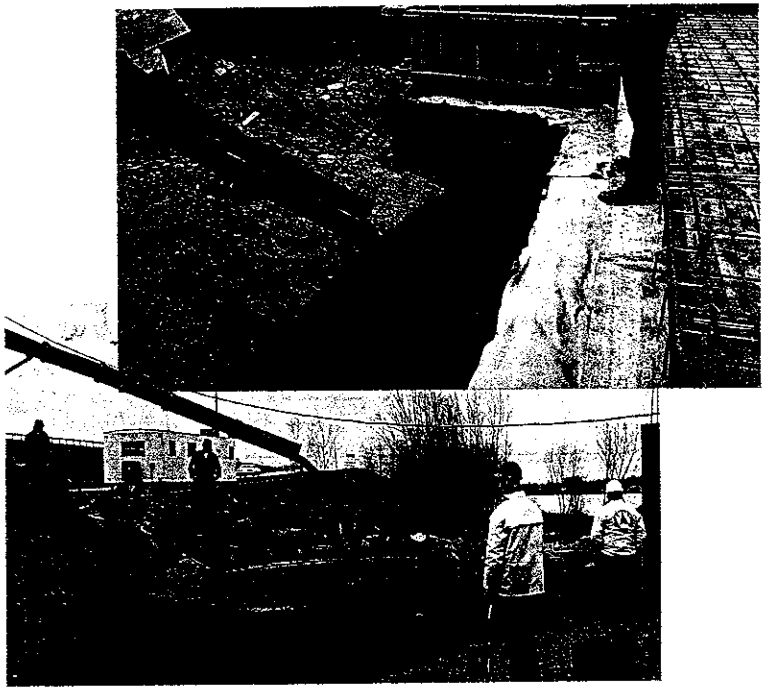

Figure 17. Bridge abutment backfill with flowable fill.

An important requirement for flowable fills in many geotechnical applications is that they can be removed with ordinary excavation equipment. From the perspective of concrete technology, this means that compressive strength should be limited to 689.5 to 1379 kPa (100 to 200 psi). Because of the combined concrete/soils technology associated with flowable mixtures, a variety of control tests have been applied to their use, including flowability as measured by a concrete slump cone or a mortar flow cone and unit weight, as well as measures of compressive strength, bearing capacity, or penetration resistance.

As with any construction application, quality control and quality assurance (QC/QA) of the materials and the mix are extremely important. Good QC/QA will take maximum advantage of the benefits of flowable fill.

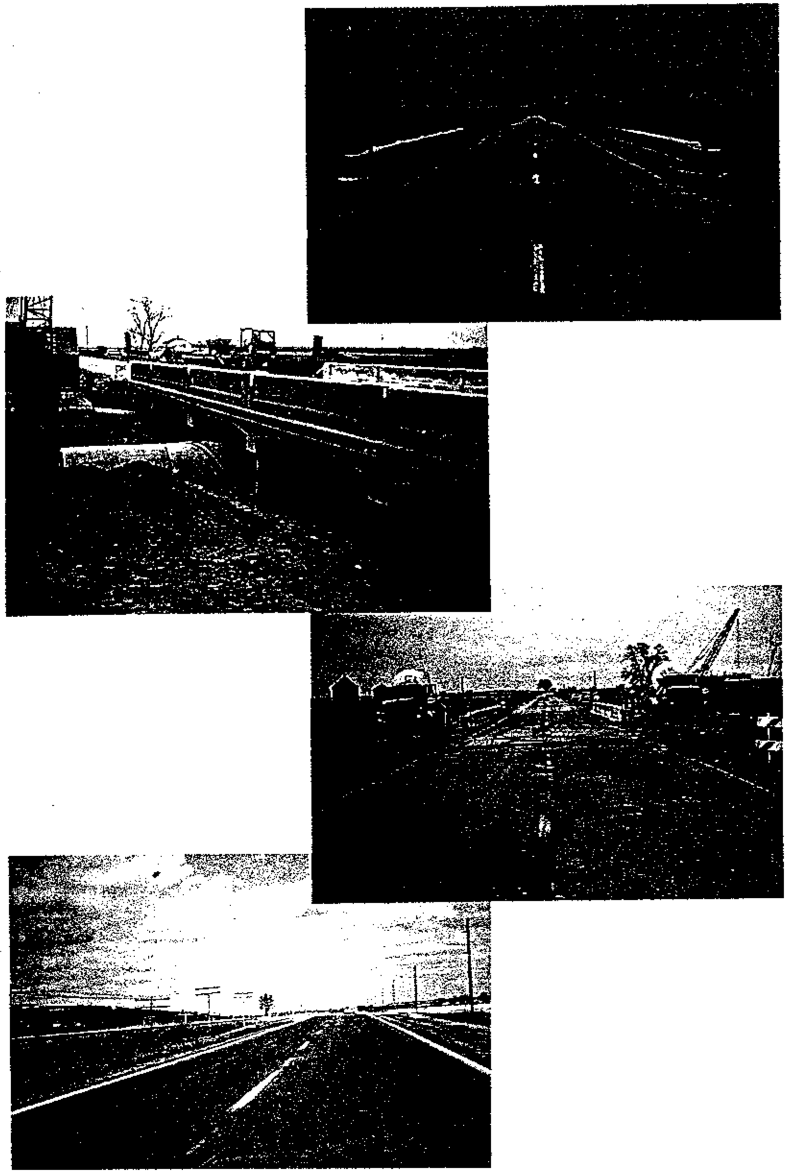

Figure 18. Bridge replaced by culverts and flowable fill.

TYPICAL MIXTURE PROPORTIONING CONCEPTS FOR FLOWABLE FILLS

Table 5. High fly ash content mixes—typical proportions.

Component	Range kg/m³ (lb/yd³)	Mix Design kg/m³ (lb/yd³)
Fly ash (95%)	949 to 1542 (1600 to 2600)	1234 (2080)
Cement (5%)	47 to 74 (80 to 125)	62 (104)
Added Water	222 to 371 (375 to 625)	247 (416)*
		1543 (2600)

*Equal to 189 liters (50 gallons)

Table 6. Low fly ash content mixes—typical proportions.

Component	Range kg/m³ (lb/yd³)	Mix Design kg/m³ (lb/yd³)
Fly ash †	119 to 297 (200 to 500)	178 (300)
Cement	30 to 119 (50 to 200)	59 (100)
Sand	1483 to 1780 (2500 to 3000)	1542 (2600)
Added Water	198 to 494 (333 to 833)	297 (500)‡
		2076 (3500)

† High calcium fly ash is used in lower amounts than low calcium fly ash.
‡ Equal to 227 liters (60 gallons)

CHAPTER 6
Use in Grouts for Concrete Pavement Subsealing

The principal requirement for a slab stabilization material is that it can flow or expand to fill very small voids and still have adequate strength to support the slab. A good stabilization material should remain insoluble, incompressible, and nonerodable after is has been placed and hardened. It should also have sufficiently low internal friction to flow into very small voids and water channels. If the material is too stiff, it will create a *seat* below the grout hole and not fill all voids. If it is too soupy, it will not have enough strength to support the slab and may have a large amount of shrinkage. Finally, it should have sufficient body to displace free water from under the slab and develop adequate strength and durability. Fly ash grout meets all of these requirements.[6]

Figure 19. Fly ash grouts for pavement subsealing.

MIX DESIGN AND SPECIFICATION REQUIREMENTS

Stabilization Materials

Fly ash-cement mixtures are recommended highly for several reasons. They are generally available within reasonable distance of most projects and are usually inexpensive. The fineness and spherical shape of the pozzolan results in a ball-bearing effect that enhances the flow properties and allows the grout to fill very thin voids. Although most of the pozzolan particles are silt-sized, they also contain a small but effective amount of clay-sized particles that provide sufficient grading to reduce segregation during pumping and injection. This results in increased durability when placed. Finally, because the hydration of cement produces lime, additional cementation occurs when the pozzolans react with the lime, which enhances the stability and produces a more effective grout.

Additives

It may be necessary to use additives or admixtures in fly ash-cement grouts to achieve the required goals. The current trend, however, is to use no additives whenever possible because of the unpredictable reactions. Laboratory tests have shown widely differing reactions from combinations of the same additive and pozzolans from different sources, and from combinations of the same pozzolan and different brands of the same additives.

Because of inconsistent reactions when using additives, the contractor should submit independent test results of chemical and physical properties as well as 1-day, 3-day, and 7-day comprehensive strength tests, flow cone times, time of initial set, and shrinkage and expansion results.

Types of additives may include accelerators such as calcium chloride to reduce set times; retarders to increase set time; expanding materials such as powdered alumina to offset shrinkage; friction reducers or pumping aids to ease pumping, increase flow, and aid in cleanup; wetting and dispersing agents to get a more uniform mixture; and water-reducing agents to lower water content. The contracting agency should allow the contractor to choose additives based on experience.

Mix Design

A typical cement-pozzolan mix design calls for 1 part cement (Type I, II, or III), 3 parts pozzolan (natural or artificial), and enough water for fluidity, usually about 1.5 to 3.0 parts water. This combination should develop sufficient strength to preclude grout erosion that could result from hydraulic action under a heavily trafficked pavement. It may be possible to reduce the cement component in some of the western, Class C ashes because they have sufficient reactivity by themselves. When this is done, the grout must still pass all the physical and chemical tests of the cement-pozzolan mix. When the ambient air temperature is between 1.7 °C to 10 °C (35 °F and 50 °F), add an accelerator to the grout mix. When calcium chloride is used, it must be thoroughly pre-mixed with the water before the addition of dry ingredients. Dry ingredients must be added in a specific ratio to increase the consistency of the grout. Do not permit stabilization using cement-pozzolan grouts when the ambient temperature is below 1.7 °C (35 °F) or when the subgrade is frozen.

Water content is determined using a flow cone and ASTM C 939. The flow cone measures the flowability of the grout mixture. The time of efflux is the flow time in seconds required to empty the cone. A time of efflux in the range of 10 to 16 seconds gives the best flowability and strengthens cement-pozzolan grout slurries.

For limestone dust slurries, the time of efflux should be 16 to 22 seconds. To ensure uniformity, the specifications should require that the consistency of the grout be checked twice daily.

The quantity of necessary water for grout flowability far exceeds the amount of water needed for hydration. Together, the roundness of the fly ash particles and the uniform gradation combine to give the grout a high permeability for its average grain size. This high permeability lets the excess water to be driven off or squeezed out during injection with a relatively low pumping pressure, which immediately makes the grout more viscous. After injection, the combination of confinement and additional excess water draining from the grout helps increase the in-place strength.

The determination of initial set time of the grout in laboratory tests is useful in comparing various mixes. Usually, the Proctor Needle Test

(AASHTO T 197) is used. Typical set times with these tests are 1-1/2 to 2 hours. However, none of the test methods considers that cement-pozzolan grouts at normal temperatures lose their fluidity within approximately 20 to 30 minutes after injection. Furthermore, because the grout is virtually always in total confinement under the slab, it is capable of supporting substantial loads before the set time indicated by these tests. Laboratory tests and field performance have shown no known pumping or displacement of the in situ grout when the traffic lane is opened within 1 hour of stabilization.

Strength

A minimum strength requirement is normally used to ensure the durability of the grout. A typical value is 4137 kPa (600 psi) at 7 days measured by the standard mortar cube test, ASTM 109. Recommendations for a pozzolan-cement grout typically suggest a 7-day compressive strength of 4137 to 5516 kPa (600 to 800 psi). The ultimate strength of the grout will be much higher (10.3 to 27.6 mPa/1500 to 4000 psi). The California Department of Transportation (CalTrans) evaluated the performance of several grouts using various cement-pozzolan ratios and determined that a 1:3 cement-pozzolan mixture with a minimum compressive strength of 5171 kPa (750 psi) at 7 days is needed to preclude erosion caused by hydraulic activity under a heavily trafficked pavement.

Finally, the contractor should submit mill certifications for the cement; chemical and physical analysis for the pozzolans; grain structure analysis for the limestone dust; and independent laboratory tests of the grout slurry. The test results should include 1-, 3-, and 7-day strengths, flow cone times, shrinkage and expansion results, time of initial set, and water retentivity.

Equipment

In the past, most stabilization contractors used batch mixers and bagged materials. Today's contractors use very mobile, self-contained units that carry all the equipment and materials needed for slab stabilization. The dry materials are packaged in either uniform-volume bags or measured by bulk weight. As stabilization procedures get more sophisticated, the trend is to automate bulk transport and metering plants because they can reduce labor and material costs by as much as 30 to 50 percent.

The small particle size and resulting increased surface area make it difficult to thoroughly wet the cement and fly ash particles with normal mixing equipment. Because of this, the contractor should use a colloidal mixer to mix cement-pozzolan grouts. Grout mixes made by these mixers stay in suspension and resist dilution by free water. The two most common types of colloidal mixers are the centrifugal pump and the shear blade. The first pulls the grout through a high-pressure centrifugal pump at high velocity. The shear blade slices through the grout at speeds between 800 rpm and 2000 rpm. The high shearing action and subsequent pressure release of these mixers remove air from the solid particles, which allows them to be wetted and make a more homogeneous mixture.

If limestone dust grouts are to be used, a paddle-type drum mixer may be substituted for the high-speed colloidal mixer. Though not recommended, paddle-type drum mixers also can be used for cement-pozzolan grouts. However, cement-pozzolan grouts made from paddle-type mixers require more water than the colloidal mixers to produce a grout with the same flowability. Grout should *never* be mixed by a conveyor, with a mortar mixer, or in a ready mix truck. Mixes made with these will require more water and the solids will agglomerate or ball up. The balled-up, partially wet clumps of grout will plug the voids at the injection hole and prevent lateral penetration.

Opening to Traffic

The time allowed before traffic can get back on the grouted slabs varies considerably. Deflection measurements taken after slab stabilization have shown that the deflections reduce over 1 to 3 hours. This is because of the hardening of the grout, which is dependent on the temperature, degree of confinement, and grout properties. It is possible to measure this change in deflection for the given job site and select a minimum opening time.

Typical specifications recommend time ranges from 30 minutes to 3 hours depending on the mix composition and the degree of confinement of the grout. Because the grout is laterally confined, experience has shown no pumping or displacement of grout when traffic has returned within an hour of stabilization. In cold weather, use accelerators in the grout to speed the initial set time.

PRODUCTION AND PLACEMENT

Material Proposal

The contractor should submit a proposal for all materials, including any additives that may be used. The proposal should include mill certifications for the cement, physical and chemical analysis for the fly ash or other pozzolans, and tests of the grout by an approved laboratory showing 1-, 3-, and 7-day strengths, flow cone times, shrinkage and/or expansion measurements, and time of initial set. The 7-day strength typically is required to be no less than 4137 kPa (600 psi) as measured using AASHTO Test Method T-106 and ASTM C 109. The test specimens must use the materials (including water and admixtures) that are to be used in the project.

Grout Plant

The grout plant usually will have a positive displacement cement injection pump and a high-speed colloidal mixing machine or paddle-type mixer. The typical colloidal mixing machine operates within a speed range of 800 to 2000 rpm to create a high shearing action for producing homogeneous mixtures.

The dry materials must be accurately measured by weight or volume if delivered and stored in bulk containers. Alternatively, the materials can be packaged in sacks containing an accurately measured amount of material for uniform batching. The water is batched through a meter or scale.

Drilling Holes

Grout injection holes are drilled in a pattern determined by the contracting agency in consultation with the contractor. They are typically no larger than 51 mm (2 in) in diameter, drilled vertically and round, and to a depth sufficient to penetrate any stabilized base and into the subgrade material to a depth of no more than 76 mm (3 in). The holes

can be washed with water or blown with air to create a small cavity to better intercept the voids within the pavement system.

Pumping and Vertical Grade Control

String lines are established above the pavement to monitor movement during subsealing. An expanding rubber packer or other approved device is lowered into the drilled holes. The discharge end of the packer or hose must not extend below the lower surface of the concrete pavement.

The pressure in the grout must be monitored by an accurate pressure gauge in the grout line that is protected from the grout slurry. Continuous grout pressures to 1379 kPa (200 psi) are typical, with pressures to 2068.5 kPa (300 psi) allowed only for short periods. In the event the pavement is bonded to the subbase, brief pressure rises (10 seconds or fewer) to 4137 kPa (600 psi) are not unusual. Allow the water displaced from pavement system voids by the grout to flow freely. Take appropriate measures to prevent excessive loss of the grout through cracks and joints or in the shoulder area.

Cautions

Pavement movements above the specified tolerances may require grinding or even removal and replacement of the pavement. Also, existing cracks in the pavement should be marked prior to subsealing operations. New cracks radiating diagonally through the grout injection holes typically will be presumed to have been caused by improper injection techniques and could result in penalties to the contractor or even removal and replacement of the pavement.

Upon completion of the subsealing, seal all drilled holes flush with the pavement surface with a fast-setting cement or other patching material approved by the engineer.

Materials Specifications

Portland cement shall meet the requirements for Types I, II, or III, per AASHTO M 85 (ASTM C 150).

Fly ash and other pozzolans. Shall meet the requirements of ASTM C 618. However, the contractor may use other pozzolans if test data meeting project specification requirements are available and the material has been used previously for this purpose on other public works projects.

Fluidity of the grout may be measured by the Corps of Engineers flow cone method or ASTM C 939. Time of efflux for pozzolanic grouts for subsealing should be 10 to 16 seconds. Use a more fluid mixture with a flow cone time of efflux of 9 to 16 seconds during the initial injection at each hole. Fluidity measurements typically are made not fewer than two times on each shift.

CHAPTER 7
Use in Fast Track Concrete Pavement

LABORATORY TESTING

It is highly recommended that laboratory testing be used to evaluate the use of fly ash. Also, evaluate the effects of temperature on the rate of hydration in the range of expected mix temperatures. As the mix temperature drops, the rate of reaction drops and could seriously alter the setting time of the concrete. Experience has shown that essentially all fly ash sources will contribute to lower water demand, improved workability, and increased long-term strength gain. Although most fast track concrete mixes have employed Class C fly ash, Class F also may produce acceptable results and may be considered after evaluation. Ground granular slag (used in the U.S. mainly along the east coast) is another feasible additive, although it has not been used in fast track concrete to date. It has been used, however, in general construction and increases early and long-term strength. This material is extremely temperature sensitive, especially at higher dosage rates. It is highly recommended that mixes employing ground granular slag be tested at the expected mix temperature ranges.

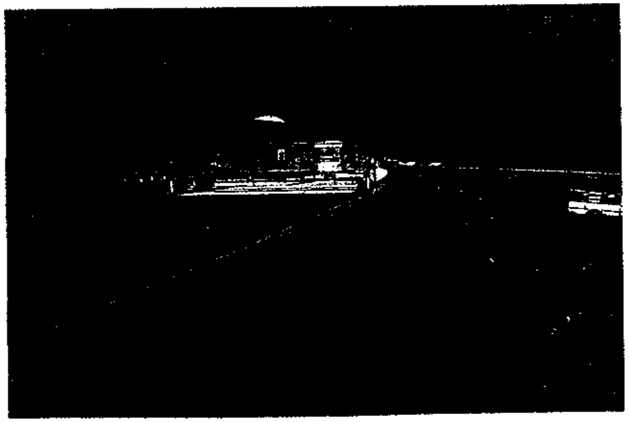

Figure 20. Fast track concrete pavements with fly ash concrete.

What are the guidelines for potential applications? The main objective in any pavement reconstruction operation is to provide a new, high-quality pavement to the public for the least cost and inconvenience. Standard specifications used by most agencies for conventional concrete mixes require opening to traffic based on strength and/or curing intervals from 5 to 14 days. Using fast track technology, concrete mixes can be designed and curing techniques used that will promote development of required opening strengths at intervals ranging from 6 to 24 hours. The result is that concrete alternatives can now be provided for projects that in the past were not considered feasible with concrete because of lengthy cure times.

In the future, fast track concrete pavement alternatives could be considered for almost all proposed projects. The merit of fast track alternatives will be determined in feasibility studies and in development of construction and traffic control staging plans. This will be true particularly where traffic patterns and access requirements along a project warrant special consideration.[7]

MATERIALS SPECIFICATIONS

Fast track concrete mixes should not require special materials or techniques. However, material selection does require more attention than for historical PCC. Local cements, additives, admixtures, and aggregates can be adapted to produce the high early strengths needed. No set mix design is required for this work.

The early strength of any mix is controlled by the water-cement ratio, cement content, cement fineness, and chemical reaction of the cementitious particles. The heat of hydration, aggregate particle distribution, entrained air, water temperature, ambient air temperature, and curing provisions must be considered for both early and long-term strength gain. The quality of fast track concrete is conducive to good durability because of the low water-cement ratio required to attain high early strengths also reduces concrete permeability.

It is recommended that a thorough laboratory analysis be conducted to determine the properties of the concrete developed with local materials before specifying a fast track (high early strength) mix design. This

testing will also verify the compatibility of all chemically active ingredients.

ADDITIVES

Fly ash and ground granular slag are often used as partial replacements for portland cement in concrete mixtures. These materials draw their benefit from the ability to react with the products of the cement/water hydration process, which helps extend the strength gain period. It should be cautioned that the effects of these materials are temperature and time dependent. Fly ash has been used in fast track concrete mixtures, although generally as an additive rather than a substitute for portland cement.

Historically, fly ash has been used to reduce the amount of cement in conventional mixes up to about 20 percent. Fly ash substitution can also be made in fast track concrete mixes using standard cements. However, to maintain early strength-gain rates, a maximum substitution rate for each source of portland cement and fly ash must be evaluated on a case-by-case basis. The fly ash is normally included with the cement in determining the water/cementitious materials ratio of the mix.

Table 7. Mixture proportioning concepts.

MIX DESIGN	CEMENT TYPE	CEMENT QUANTITY	TARGET W/C RATIO	FLY ASH	COARSE AGGREGATE	FINE AGGREGATE	ADMIXTURES AE*	WR†	AC‡
A	I	380 (641)	n.a.	73 (123)	843 (1420)	843 (1420)	YES	YES	NO
B	II	390 (658)	0.39	0 (0)	1008 (1698)	679 (1145)	YES	YES	NO
C	II	390 (658)	0.39	99 (167)	935 (1575)	630 (1062)	YES	YES	YES
D	III	421 (710)	0.373	0 (0)	907 (1528)	806 (1358)	YES	YES	NO
E	III	380 (640)	0.425	70 (118)	838 (1413)	838 (1413)	YES	YES	NO
F	III	380 (640)	0.425	70 (118)	838 (1413)	838 (1413)	YES	YES	NO
G	III	380 (641)	0.425	73 (123)	839 (1414)	836 (1409)	YES	YES	NO
H	III	441 (743)	0.40	82 (138)	776 (1308)	779 (1313)	YES	YES	NO

*AEA = Air entraining admixtures
†WR = Water reducer
‡AC = Nonchloride accelerator

n.a. = not available
kg/m^3 (lbs/yd^3) = kilograms per cubic meter (pounds per cubic yard)

CHAPTER 8
Use in Structural Fills/Embankments

SPECIFICATION REQUIREMENTS

General

Specifications are required to ensure that the fly ash embankment will possess the strength and compressibility requirements that were assumed during design. Either method or performance specifications can be written for the compaction of fly ash.[8,9]

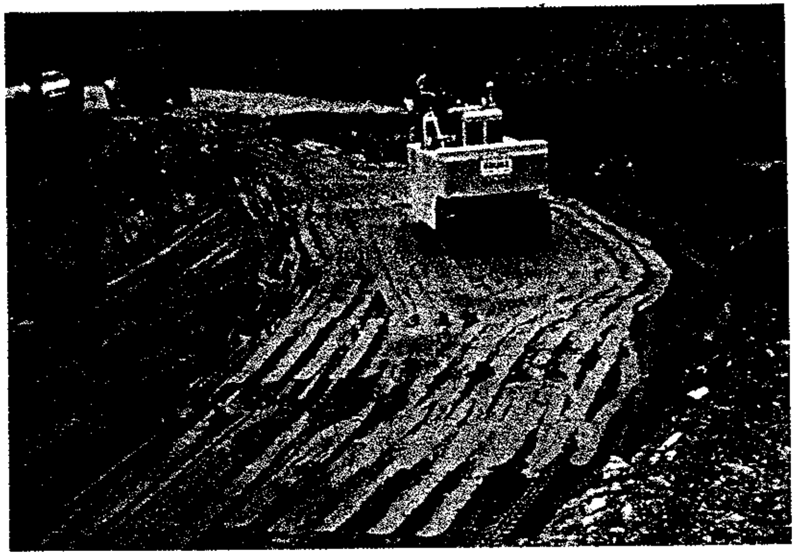

Figure 21. Highway embankment with fly ash structural fill.

Ash sources. Fly ash can be hopper, silo, lagoon, or stockpiled ash. Hopper or silo fly ash can be delivered with close limitations on moisture content and grain size distribution. Conversely, the moisture content or grain size distribution of lagoon or stockpiled ash can vary considerably depending upon its location within the lagoon or stockpile.

Therefore, using lagoon or stockpiled ash may require several series of laboratory tests. If fly ash from more than one source is being used on the project at the same time, it is preferable to place and compact the ashes separately. Because of its self-hardening properties, high calcium ash is typically stored in silos and hauled to the construction site in pneumatic tank trucks. This procedure may not be necessary if the site is close enough to the plant to allow the ash to be hauled in the moistened condition.

Compaction/quality control. The two types of specifications written for fly ash embankments are performance specifications and method specifications. Performance specifications state the required degree of compaction and allowable moisture content range. For road embankments, a typical requirement is to compact the fly ash to 95 to 100 percent of maximum dry density, as determined by AASHTO Method T99-81. Determine the allowable range for the moisture content by plotting the laboratory moisture-density relationship as shown in table 8, page 65. Fly ash may be variable enough that several curves are required. It is preferable to place the ash at less than optimum moisture because the compactive effort applied by construction equipment may exceed the compactive effort applied in the laboratory.

On some projects, method specifications are preferable to performance specifications. The method specification is based on the results of field compaction tests on trial strips. The lift thickness, weight of compaction equipment, speed of compaction equipment, and the number of passes must be evaluated so that the fly ash achieves the necessary degree of compaction. If vibratory compaction equipment is being used, the resonant frequency of each compactor in use must be established in the field. The method specification allows for simpler quality control because the compaction procedures can be monitored visually.

CONSTRUCTION PRACTICES

General. Recommended construction procedures have been developed as the result of experience gained with trial embankments and construction projects. Adjustments to these standard procedures will be necessary, depending on actual field conditions.

Site preparation. Preparing the site for fly ash placement is similar to requirements for soil fill materials. The site must be cleared and grubbed. Topsoil should be retained for final cover. Give special attention to draining the site and to preventing seeps, pools, or springs from contacting the fly ash.

Delivery and on-site storage. Fly ash is usually hauled to the site in covered dump trucks, pneumatic tanker trucks, or ready mix trucks. Adjust the water content of the ash to prevent dusting. In the case of lagoon ash, reduce the water through temporary stockpiling and/or mixing with drier silo ash to prevent road spillage during transport and to allow proper placement. Because of the self-hardening properties of high calcium ash, it is stored dry in silos or pneumatic tanker trucks. Low calcium ash can be stockpiled on-site if the ash is kept moist and if the ash is covered to prevent dusting and erosion.

Spreading. Fly ash is usually spread and leveled with a dozer in loose lifts 152 to 305 mm (6 to 12 in) thick. The lift is then tracked with the dozer for initial compaction.

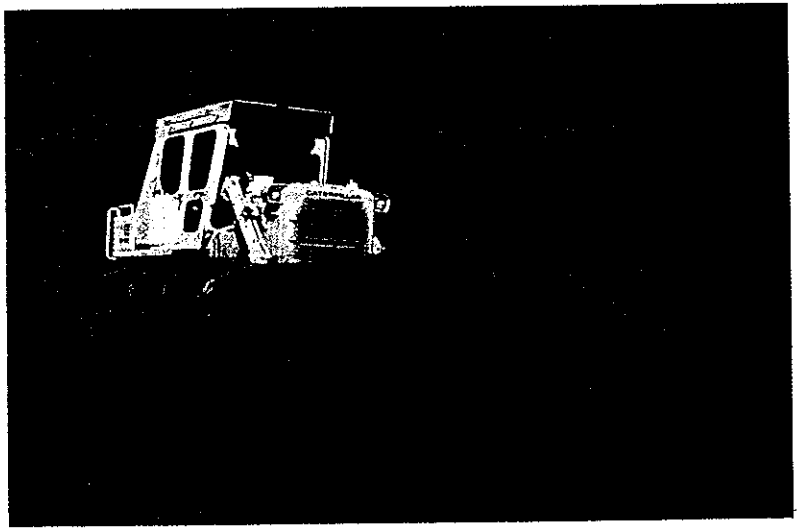

Figure 22. Spreading fly ash structural fill.

Compaction equipment. Begin compaction as soon as the material has been spread and is at the proper moisture content. The most successful compaction results have been achieved with self-propelled, pneumatic-tired rollers and self-propelled or towed vibratory rollers. Table 8, page 65, is a list of the types of compaction equipment that have been tested for use with fly ash.

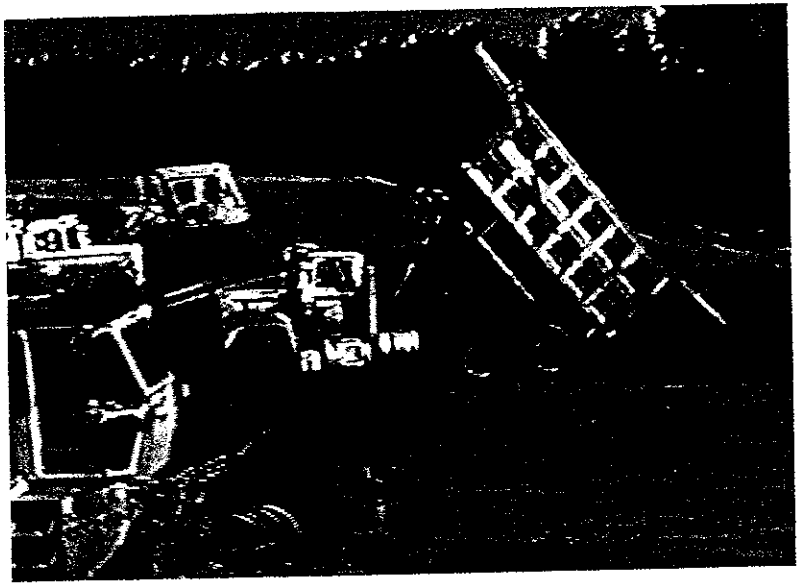

Figure 23. Compaction of fly ash structural fill is crucial, as with any backfill material.

Moisture control. Control of the required range of moistures is an important consideration in the compaction procedure. Be sure to compare the alternatives of hauling fly ash moistened to the desired water content at the plant, or adding water at the site. Hauling moist fly ash to the site means higher transportation costs, while adding water on-site sacrifices productivity in field placement.

Weather restrictions. Fly ash can often be placed during inclement weather. In the winter months, frost usually penetrates only the upper layer of the compacted ash, which can be recompacted upon thawing. During compaction, if the water freezes too fast, the operation should be suspended until the temperature rises. Construction can also proceed during wet weather even if the moisture content of the ash is too high. However, the equipment may bog down and it may be difficult to achieve proper compaction.

Insensitivity to moisture variations. Because water is added to low calcium fly ash during unloading from storage silos, it can be obtained at any moisture content that is desired. Although the optimum moisture content is greater than that of silty soils, the compaction behavior of low calcium fly ash is relatively insensitive to variations in moisture content when placed dry of optimum. High calcium fly ash, however, will self-harden when water is added and becomes difficult to handle if not placed in a timely manner.

What do I have to do?

1. ***Assess availability.*** Contact the local electric utility or ash broker to determine whether an adequate supply of fly ash can be provided in the time frame required.

2. ***Investigate site conditions.*** As with any embankment project, use standard geotechnical techniques to evaluate subsurface soil and groundwater conditions. The two most important subsurface characteristics affecting embankment construction and performance are shear strength and compressibility of the foundation soils.

3. ***Evaluate the physical, engineering, and chemical properties of the ash.*** The physical and engineering properties of fly ash that will determine the behavior of the embankment are grain-size distribution, moisture-density relationships, shear strength, compressibility, permeability, capillarity, and frost susceptibility. Laboratory tests designed for testing soil properties apply equally well to testing fly ash. The chemical characteristics of the fly ash affect the physical behavior as well as the quality of the leachate produced by the ash. The utility company or its marketing agent can provide information on the physical, engineering, and chemical composition of the ash and leachate characteristics.

What other factors should be considered? The mechanical behavior and compaction characteristics of fly ash are generally similar to those of silt. Conversely, fly ash also shares some of the difficulties that are characteristic of silt such as dusting, erosion, piping, and frost susceptibility. These difficulties can be properly addressed during the design of the embankment. For example, ice lenses grow in silt-sized soils by wicking water up from a shallow groundwater table. Such ice lenses expand during the winter and melt during the spring causing unstable and soft embankment conditions. The problem can be avoided by controlling upward seepage with a layer of coarse-grained material or geotextile at the base of the embankment. In general, avoid using fly ash as a borrow material below the groundwater table or when the embankment design cannot provide adequate drainage.

What about environmental impacts? The trace element concentrations in many fly ashes are similar to those found in naturally occurring soils. Although the leachates of some fly ashes may contain trace element concentrations that exceed water quality standards. This is true of certain soils. State environmental regulatory agencies can guide you through applicable test procedures and water quality standards. The amount of leachate produced can be controlled by assuring adequate compaction, grading to promote surface runoff, and daily proof-rolling of the finished subgrade to impede infiltration. When construction is finished, a properly seeded soil cover will reduce infiltration. For highway embankments, the pavement itself is an effective barrier to infiltration.

Erosion and dust control. To prevent wind and surface water erosion of the fly ash embankment, use the same sediment and erosion control techniques common during earthwork operations. This includes wetting down exposed surfaces and installing silt fences or straw bales around construction areas. Dusting will likely occur when compacted fly ash is placed in dry, windy, or freezing weather, or during traffic disturbance. During construction, the surface should be kept moist, covered, or stabilized with lime or bitumen. To prevent erosion and dusting after completion of the embankment, protect the fly ash with topsoil and vegetation or by sealing with bituminous emulsion.

Where can I go for more guidance? The Federal Highway Administration has participated in several demonstration projects to document the behavior of fly ash structural fills and embankments. The American Coal Ash Association is an excellent source for information on

other projects, as well as on fly ash characteristics and behavior. The Electric Power Research Institute has published several design and construction manuals on fly ash use in highway construction. Finally, the American Society for Testing and Materials (ASTM) has published a guide for the use of coal combustion fly ash in structural fills.

Table 8. Combinations required for 95 percent of the standard proctor maximum dry density, AASHTO Method T 99-81.[10]

Equipment	Thickness	Passes	Comments
Vibratory Smooth Drum Roller (1 to 1-1/2 tons) (900 to 1350 kg)	150 mm (6 in)	≤8	May slightly overstress surface; compaction may only reach 90 percent
Vibratory Smooth Drum Roller (6 to 10 tons) (5400 to 9100 kg)	150-300 mm (6-12 in)	≤8	9100 kg (10 ton) roller may need as few as 3 passes at lower lift thicknesses; may overstress surface
Vibratory Smooth Drum Roller (10 to 20 tons) (9100 to 11,000 kg)	200-300 mm (8-12 in)	4-6	May seriously overstress surface; ballast reduction and frequency change will reduce this problem
Pneumatic-tired Roller (10 to 12 tons) (9100 to 11,000 kg)	150-300 mm (6-12 in)	≤8	Limit tire pressure to 250 kPa (35 psi); provides good smooth surface seal
Vibratory Padfoot Roller (6 to 20 tons) (5400 to 9100 kg)	150-300 mm (6-12 in)	≤8	Pad height should be roughly 100 mm (4 in) or less, pad area should be greater than 7750 mm^2 (12 in^2)
Vibrating Plate Tamper (large plate)	200-250 mm (8-10 in)	2-3	Used in confined areas and where ground loading must be kept low (e.g., backfills)
Sheepsfoot			Not recommended
Grid Roller			Not recommended

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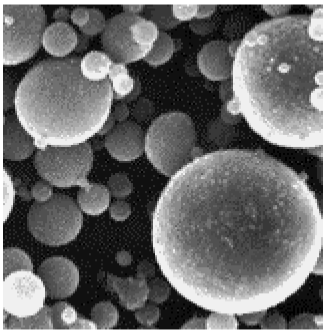
TECHNICAL DATASHEET NO. 2

PULVERISED FUEL ASH FOR FILL APPLICATIONS

Introduction

There are a considerable number of advantages in using pulverised fuel ash (PFA) or fly ash, as it is known in many countries, as a fill material over naturally occurring materials as follows. PFA is beneficial for the following reasons:

- It is lightweight when compared to most materials, as shown in figure 1. This leads to savings in material, transport costs and reduces settlement in underlying soils.
- When properly compacted, PFA settles less than 1% during the construction period with no long-term settlement.
- The self-hardening properties of some PFA's offer considerable strength advantages over natural clay and granular materials.
- They can exceed the design strength immediately after compaction.
- The immediate strength of PFA means simple shallow trenches have a reduced need for shoring.
- With proper profiling PFA fill can be trafficked in all weathers.



The types of PFA available

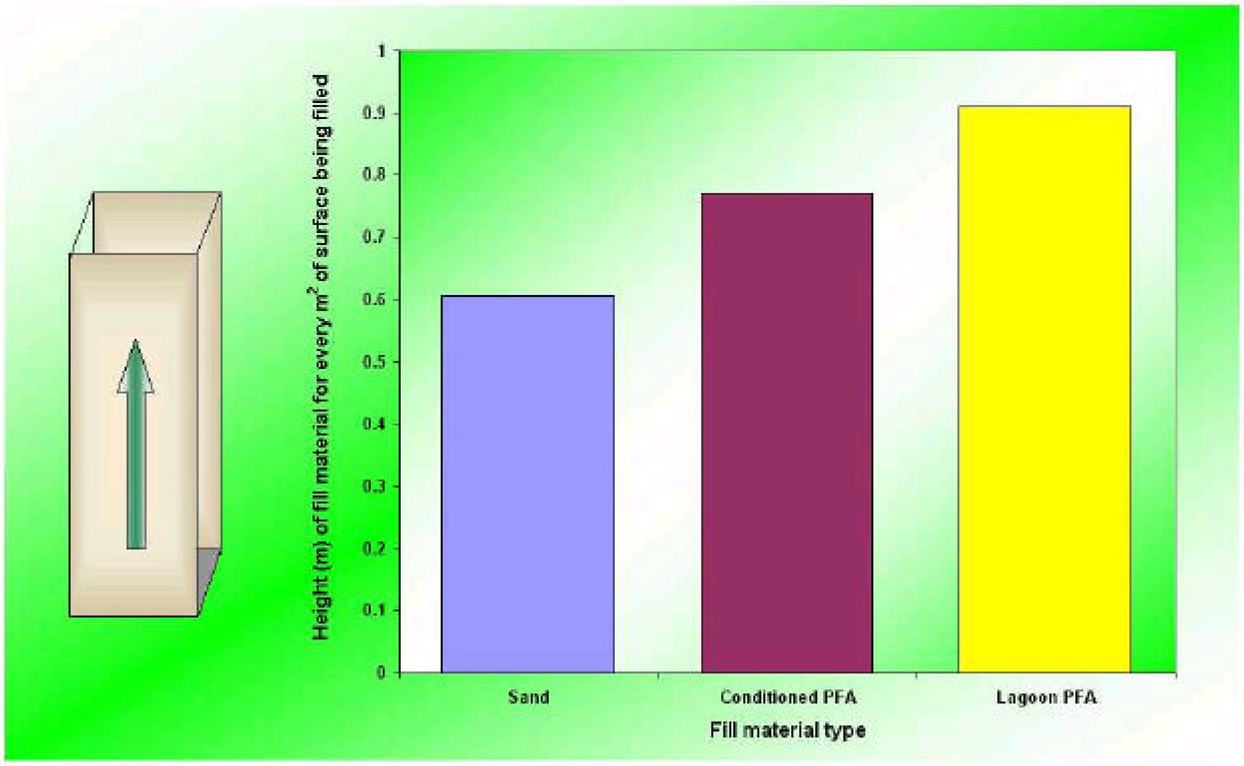
There are three types of PFA readily available for use as a fill material:

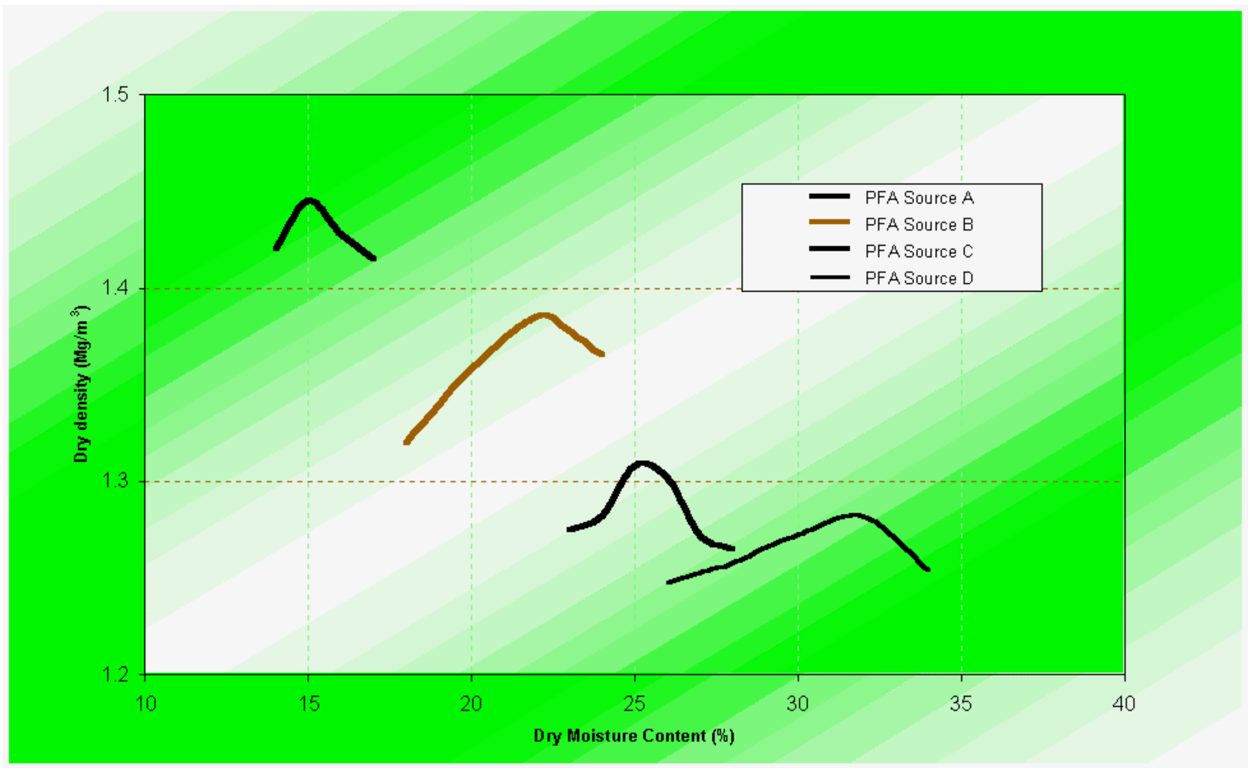
- **Conditioned ash** – PFA taken directly from the silos at the power station to which a controlled amount of water is added to assist in handling, dust prevention and compaction on site.
- **Stockpiled ash** - Previously conditioned PFA that has been stockpiled prior to use.
- **Lagoon Ash** – PFA which has been slurried and pumped to storage lagoons. It is then allowed to settle and drain before delivery. Lagoon ash is somewhat coarser than conditioned ash.

The Properties of PFA

PFA is usually placed in accordance with the Department of Transport Specification for Highway Works that classifies it as a cohesive material for general fill (type 2E) or as a structural fill (type 7B). All PFA is suitable for general fill but only conditioned PFA is considered by the Highway's Specification as being suitable for structural fill. This is considered to be restrictive and preferably it should be specified in terms of its properties and not type.

The following information is based on typical values and provided for guidance only. The actual values for any source can be obtained by contacting the supplier.





Optimum Moisture content

The moisture content of PFA is an important factor in achieving the desired compaction and density values. The optimum moisture content varies from source to source as in figure 2. In general conditioned PFA requires lower moisture content to achieve full compaction than lagoon ash. In practice sufficient compaction can be achieved over a range of moisture contents between 0.8 and 1.2 times the optimum value. Though the supplier adds water to PFA some variation in moisture content will occur especially during hot weather or when the PFA has been stockpiled on site prior to placing. It is recommended that provision be made to add water on site at the time of placing.

Strength – PFA is defined as a cohesive material, with the shear strength increasing with time with most ashes. PFA is placed in a partially saturated condition but may become saturated at later stages, which will reduce the measured strength. Therefore, it is important that all strength tests are carried out on saturated samples. Strength can be measured in many ways:

- The DOE specification requires peak shear parameters based on saturated shear box tests. The proposed values are: c'_{peak} = 5 kPa and f '$_{peak}$ = 30° . However, it is recommended that guidance on the actual values be sought.
- CBR is often used in road design. CBR values tend to rise with time increasing the factor of safety.
- Design is normally based on strength at zero days. Typical low bound values for inundated ash at zero days are:
    - Peak shear cohesion - 0 kPa to 20 kPa
    - Peak shear friction angle - 26° to 35°
    - Critical state - c'_{crit} = 0, f '$_{crit}$ = 26° to 30°
    - CBR - 10% to 20%

Stiffness - Providing the PFA has been adequately compacted there are no long-term settlement problems. Even poorly compacted PFA has been shown not to settle to any significant extent. Any settlement will occur during construction. The m_v value is typically 0.1 to 0.4 m^2/MN.

Air voids – PFA has a higher air voids content than conventional fill materials. Typically air contents range from 8 to 20%. Consequently, the use of maximum air voids limits may not be appropriate.

Permeability - Even though PFA has a relatively high air content it can be considered comparatively impermeable; typical k values are:
2×10^{-5} to 3×10^{-7} m/s
Normal rainfall may be held in the air voids without saturation occurring. If the PFA does become saturated then it will soon recover if left. The low permeability prevents leaching of soluble material from the mass of the compacted material. PFA would normally be categorised as a Class 2 to 3 sulfates material (BS5328). However, the sulfate is mainly present as gypsum, which has a limited solubility. BRE Digest 363 acknowledges that low permeability materials can reduce the risk of sulphate attack and in many instances allows PFA to be set in Class 2. There has been no reported incidence of sulphate attack on adjacent concrete structures, even after 25 years of exposure.

Frost Heave - Water may rise by capillary action in PFA even after compaction. A drainage layer of coarse material 150 - 450mm in depth should be placed below the PFA to eliminate capillary action consisting of Furnace Bottom Ash, free draining stone or a geotextile membrane. The capillary action does make PFA, like all fine-grained silts and clays, frost susceptible. Lagoon ash and stockpiled PFA mixed with a coarser material are only slightly frost susceptible, if at all.

Compaction – PFA fill is normally placed in layers of up to 225mm thick compacted down to 150mm. Widely available compacting plant can be used – see our Best Practice Guide No.2. Typically 6 - 8 passes is sufficient to fully compact each layer. Though the Specification for Highway Works requires at least 95% of the maximum dry density, historically 90% has been accepted by many sites as being satisfactory. This has been confirmed by recent research, providing the moisture content is less than the optimum value.
The maximum dry density and optimum moisture content should be determined using the 2.5 kg rammer as described in BS1377 Part 4. As with any fill material there is some variability in the maximum dry density of PFA from a given source and regular testing is required.

Site Operations

As with all site operations careful planning will pay dividends. We would recommend the following:

- PFA should be delivered in sheeted vehicles to prevent moisture loss and environmental problems.
- Spread the PFA in loose layers not exceeding 225mm thick.
- Compaction is normally achieved by a towed or self-propelled vibratory roller or pneumatic-tyred rollers. Six to eight passes are normally required.
- If water is to be added this should be sprayed uniformly over the surface before compaction. Back tining may be used to encourage an even distribution throughout the full depth of the layer. A water bowser is the most suitable means of obtaining a uniform distribution.
- The surface must be finished to a fall to ensure adequate surface drainage.
- If end product control is used then density tests should be carried out on the penultimate layer. The test rate is usually 1 test per $200m^3$ ($1350m^2$ for 150mm thick layers) for small projects and 1 test per $500m^3$ ($3500m^2$ for 150mm layers) for larger projects.
- If PFA is stockpiled on site care must be taken to prevent drying out.
- If one fails to achieve the density criteria the tests should be repeated and the maximum dry density checked. The 2.5kg rammer should be used.
- If the surface becomes wet due to heavy rain the surface should be allowed to dry out, or if necessary the top 150mm can be removed and replaced. The removed material may be reused when it has dried out sufficiently.

Site Testing

Measurement of density can be made using core cutter equipment. However, in some instances the PFA can become so stiff that is difficult to drive the mould in without disturbing the sample. If this occurs the sand replacement method should be used. Nuclear density techniques have been used but care must be taken in determining moisture contents.

Other applications
Cement or lime stabilised PFA - Road bases, sub-bases and hard shoulders can be constructed in insitu using cement or lime stabilisation. See our 6 series datasheets on Fly Ash Bound Mixtures (FABM).

Landscaping – PFA has been widely used for landscaping derelict areas. It will support, with modest encouragement, a variety of vegetation. Methods of establishing cover range from Hydroseeding to applying topsoil or subsoil. An application of fertiliser or a first sowing of clover or other suitable crop will redress the deficiencies in nitrogen and organic matter.

Remediation of contaminated ground – PFA being a low permeability, pozzolanic material can be used to contain contaminants in brown field sites. Figure 6 shows a multiple auger technique being used to prevent leaching from contaminated waste.

(In general usage the term 'fly ash' is used for pulverised coal ash but it can also cover ash from burning other materials. Such 'fly ash' may have significantly differing properties and may not offer the same advantages as ash from burning pulverised coal. UKQAA datasheets only refer to PFA / fly ash produced from the burning of coal in power stations.)

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TECHNICAL DATA SHEET 6.0

FLY ASH BOUND MIXTURES (FABM) FOR ROAD & AIRFIELD PAVEMENTS

Gotham by-pass, Notts. Levelling / Laying CFA. Gotham by-pass, Notts. Levelling / Laying CFA. Gotham by-pass, Notts. compacting CFA.

Definition

FABM is a construction material for pavements that is a mixture of pulverised fuel ash (PFA) and one or more other components whose performance relies on the pozzolanic properties of the PFA.

Objectives

- to make more extensive use of PFA, a by-product from coal-fired power generation plants
- to reduce the consumption of primary materials for pavement construction
- to widen the range of pavement construction materials
- to produce cost, as well as environmentally, effective pavements.

Field of application

Capping, sub-bases and road bases of all classes of road and airfield pavements & footways.

Characteristics, performance and durability

PFA is a pozzolanic material, which thus, in the presence of lime [CaO or $Ca(OH)_2$], hardens under water. Compared to ordinary Portland cement, the rate of hardening of the PFA/lime combination is more protracted. This has advantages in pavement construction.

- in the short term, FABM have extended handling times and thus the flexibility of unbound granular pavement materials.
- in the long term, FABM develop significant stiffness and strength with the performance and durability of bituminous and cement-bound materials.

Where quicker hardening is required, say in cold weather working, partial or complete replacement of lime with cement or the addition of gypsum or other suitable material can be employed.

Quality of the PFA

Dry, conditioned or lagoon PFA can be utilised for FABM. The PFA need not be fresh. The utilisation of old PFA is perfectly acceptable and indeed may be advantagous. The requirements are attached but essentially, a significant proportion of UK ashes, old or new. are suitable.

Examples:

Examples of FABM are shown in table 1. This table has been extracted from the draft European standard for FABM for road construction, currently under preparation. It should be noted that the list of FABM shown in the table is not intended to be exhaustive but illustrative of the current use of FABM in Europe. Data sheets on some of the FABM illustrated are available

Manufacture

With respect to the quality of the finished product, FABM are preferably and generally produced in central batching plants utilising pug-mill continuous mixers, although the use of other stationary mixers and the mix-in place method of construction can be employed in certain situations.

Laying

Placement and compaction is by conventional plant such as drot, grader, paver and vibrating roller. Pneumatic-tyred rollers are usually specified for finishing purposes and for some FABM, as the only means of compaction. Immediately after compaction, FABM shall be prevented from drying out by the application of an alkaline bitumen emulsion or the repeated light-spray application of water. The slow rate of hardening of FABM ensures good workability, immediately trafficability and some capacity of self-healing.

SPECIFICATION FOR PULVERISED FUEL ASH (PFA) FOR FLYASH BOUND MIXTURES (FABM) FOR ROAD &AIRFIELD PAVEMENT

1. SCOPE

This specification applies to PFA for use in fly ash bound mixtures (FABM) for roadbase, sub-base and capping.

2. REFERENCES

- BS EN451-2 Method of testing fly ash- Part 2 : Determination of fineness by wet sieving.
- BS EN196-2 Loss on ignition.
- BS EN451-1 Method of testing fly ash - Part 1: Determination of free calcium oxide.
- BS EN193-3 Soundness.

3. DEFINITIONS

1. **PFA** Fine powder produced by the combustion of pulverized coal in energy generating plants and captured by mechanical or electrostatic precipitators. The essential chemical components are silicates, aluminates and iron oxides. The PFA is a pozzolanic material. It can be stored, supplied and used either in a wet (conditioned) or dry condition.
2. Pozzolanic **Material** Material which sets and hardens with lime [$Ca(OH)_2$ or CaO] in the presence of water to form stable and durable compounds.
   Dry PFA For the purposes of this specification, dry PFA means a PFA which contains less than 1% water by dry weight.

4. REQUIREMENTS

1. **Particle Size** Particle size, carried out in accordance with BS EN451-2, shall conform with the following:

Sieve	% by Mass Passing
90 micron	>= 70%
45 micron	>= 40%

2. **Chemical composition** Expressed as a percentage by mass of the dry product, which is obtained by drying a laboratory sample in a well ventilated oven at 105 ± 5 degrees C to constant weight, and cooled in a dry atmosphere.
3. **Loss on ignition (LOI)** The LOI, measured in accordance with BS EN196-2, but using an ignition time of 1 hour, or other equivalent method, shall not exceed 8% by mass, except where proportion-wise, the PFA is the main component in the FABM when the LOI shall not exceed 10%.
   NOTE: The purpose of this requirement is to limit the residue of unburnt carbon in PFA. It is sufficient therefore, to show through direct measurement of unburnt carbon residue, that it is less than the value specified above.
4. **Sulphate content** The sulphate content, expressed as total S03, shall not exceed 4% by mass when measured in accordance with BS EN196-2.
5. **Free calcium oxide content** The free calcium oxide content, measured in accordance with BS EN451-1, shall not exceed 1% by mass. If this requirement is not met, soundness shall be measured in accordance with BS EN196-3, and the expansion shall not exceed 10mm with a 50:50 blend of PFA and cement.
6. **Water content** Dry PFA shall contain not more than 1% mass of water. PFA can be stored, used and supplied either in a wet or dry condition.

Table 1 Examples of fly ash bound mixtures (FABM) for road and airfield pavements

Type of FABM	**Abbreviation**	**Typical proportions as a percentage of dry mass (%)**								
		Conditioned PFA	**Lime (CaO)**	**Pc**	**Graded crushed coarse material**	**Sand**	**Soil/ earth**	**Other material**	**Typical Water content %**	**Normal age of performance testing (days)***
Lime PFA	LFA	93-97	3-7						15-25	90
Lime gypsum PFA	LFA	91	4					5% gypsum	"	"
Cement PFA	CFA	90-95		5-10						28
Lime PFA granular material	GFA	8.5-13	1.5-3		50-55	30-40			6-8	0
"	"		1**		50-55	40-45		4-6% dry PFA	"	"
Cement PFA granular material	"	3-6		1-3	50-55	40-45			"	28
Slag PFA granular material	"	5-7	0-2		50-55	30-40		5-7% GBS***	"	90
Lime PFA sand	SFA	9-12	2-4			84-89			Approx. 10	"
Cement PFA Sand	"	6-8		2-4		88-92			"	28
Lime PFA earth (soil)	EFA		1-2**				0-93	6-8% dry PFA	Depends on soil	90
Cement PFA earth	"	3-6		2-4			91-94		"	28

* Earlier age testing is permissible subject to data and experience. **Lime is usually pre-blended with PFA.
*** Granulated Blastfurnace Slag

(Pulverised Fuel Ash (PFA) is also known as 'fly ash' in European Standards and in many countries. Fly ash can refer to ashes produced from furnaces other than those from coal burning power generation. Such fly ash may have significantly differing properties and may not offer the same advantages as PFA. The UKQAA datasheets only refer to PFA/fly ash produced from the burning of hard bituminous coal within power station furnaces.)

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TECHNICAL DATA SHEET 6.1

LIME/FLY ASH BOUND GRANULAR MATERIAL (GFA) FOR ROAD AND AIRFIELD PAVEMENTS



A52 Froghall, Staffs. Laying GFA. A52 Froghall, Staffs. Compaction of PGFA. A52 Froghall, Staffs. Blending plant.

Definition

GFA is a mixture of crushed graded coarse material, sand, pulverised fuel ash (PFA), lime and water, where the PFA and lime combination performs as a binder.

Objectives

- to make more extensive use of PFA, a by-product from coal-fired power generation plants
- to reduce the consumption of primary materials for road construction
- to widen the range of road construction materials
- to produce cost, as well as environmentally, effective pavements

Field of application

Sub-bases and roadbases of all classes of road & airfield pavements and footways.

Characteristics, performance & durability

GFA is a slow hardening mixture, which progresses from an unbound crushed stone material into a bound paving material, the rate of reaction being strongly dependent upon temperature (see Figure 1). This has advantages in road construction,

- in the short term, GFA has a handling time of many hours and thus the flexibility of unbound granular paving materials;
- in the long term and depending on the aggregate, GFA develops significant elastic stiffness (10-30 GPa) and tensile strength (1-3MPa) and thus results in a pavement material with the performance and durability of bituminous and cement-bound materials.

The following characteristics should also be noted:-

- the slow reaction rate realises extended workability, permits immediate accessibility to site traffic and the capacity of self-healing
- in the fresh condition on normal sites, the correct grading framework for the GFA produces a tight closed finish that can withstand rain
- on hilly sites, the fines in the fresh GFA can be removed by running water and measures should be taken to prevent this occurring
- the use of crushed material and the correct grading framework is responsible for the immediate traffickability of GFA and thus the stability of GFA over the short and medium- term which permits the stiffness and strength of GFA to develop unimpaired
- the ultimate structural characteristics may not be achieved until 2 to 3 years after laying
- the slow reaction rate generally limits construction to the period April to September inclusive to enable frost resistance to be achieved before the first frosts. Outside this period, partial or complete replacement of lime with cement or the addition of gypsum or other suitable material can be employed

Mix composition

Typically, mix proportions, as a percentage of dry weight, will be similar to one of the following:

Mix composition

Conditioned PFA	Dry PFA	Lime (CaO) or $Ca(OH)_2$	20-5mm** graded crushed agg	5-0mm sand**	Water Content
8 to 13	N/A	1.5 - 3	47 - 53	32 - 38	6 - 8
N/A	4 - 6*	1 - 1.5*	50 - 56	40 - 45	5 - 7

* lime and dry ash preblended at works

** natural, reclaimed or by-product material

Manufacture

GFA is produced by weight in central batching plants equipped with continuous pug-mill mixers.

Laying

Placement and compaction is by conventional plant such as drot, grader, paver and vibrating roller. Pneumatic-tyred rollers are usually specified for finishing purposes. Immediately after compaction, GFA shall be prevented from drying out by the application of an alkaline bitumen emulsion or the repeated light-spray application of water.

Utilisation

- GFA can be used as sub-base/roadbase under bituminous or pavement quality concrete surfacing in either case, the GFA shall be laid on a subgrade, capping or sub-base material with a soaked laboratory CBR of at least 15%
- the thickness of GFA and surfacing is a function of the ultimate structural properties of the GFA and traffic and shall be determined by an experienced pavement engineer

A recent application

In 1997, GFA was used for the reconstruction of a 1 km length of the A52 in Staffordshire. The job consisted of the removal of 400mm depth of existing pavement material, recycling off-site with pfa and quick lime, and relaying as a 300mm GFA layer under 100mm of new bituminous surfacing.

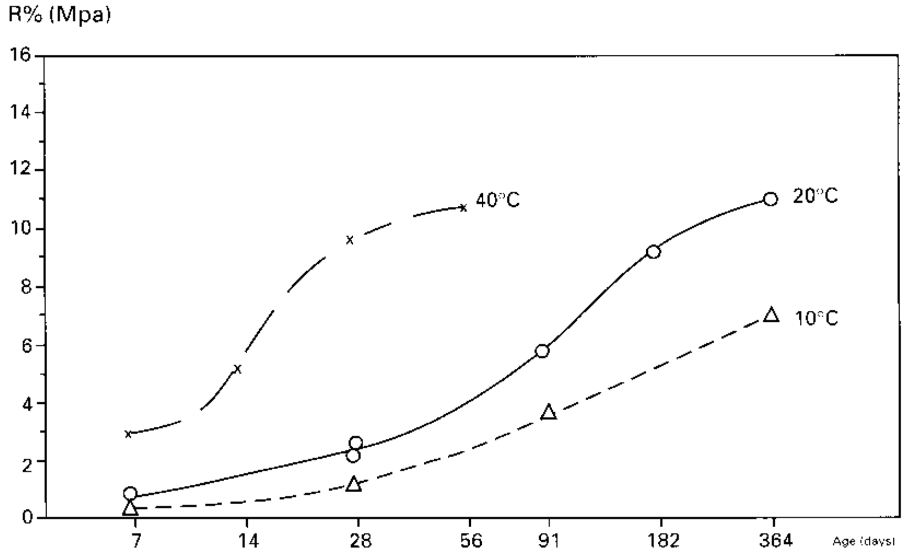

Figure 1. Development of the unconfined compressive strength of GFA.

(Pulverised Fuel Ash (PFA) is also known as 'fly ash' in European Standards and in many countries. Fly ash can refer to ashes produced from furnaces other than those from coal burning power generation. Such fly ash may have significantly differing properties and may not offer the same advantages as PFA. The UKQAA datasheets only refer to PFA/fly ash produced from the burning of hard bituminous coal within power station furnaces.)

UNITED KINGDOM
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TECHNICAL DATASHEET NO. 6.4

Pulverised Fuel Ash in Cement Bound Mixtures

Introduction

CBM 3, 4 and 5 are categories of Cement-Bound Materials that are specified in the Department of Transport's 'Specification for Highway Works' (SHW) for use in trunk road and motorway pavements.
In accordance with the Department Of Transport's, 'Design Manual for Roads and Bridges, Volume 7';

- **CBM 3 is the specified sub-base for concrete pavements across the full range of traffic densities.**
- **CBM 3, 4 and 5 are permitted roadbase for traffic up to 80 million standard axles.**

In addition, the relevant authorities for airfield and port pavements also specify CBM 3, 4 and 5.

The Use of PFA / fly ash in CBM

The structural and cost benefits from the use of Pulverised Fuel Ash (PFA), or fly ash as it is known in many countries, in CBM have long been recognised and employed. This data sheet quantifies explains the benefits and gives advice on the use of dry or conditioned, fresh or stockpiled PFA in CBM (See Data Sheet 6 for the PFA specification). Our East Midlands Airport Case study is a particularly good example of the use of CBM for an airfield sub-base.

Strength Development of CBM with PFA

The benefits relate to the more progressive strength development that PFA gives CBM. The rate of strength gain beyond 7 days is usually much higher than with straight Portland Cement (CEM I as per EN197-1 2000) mixtures. See Technical Datasheet No. 1 for an explanation of this effect. The Notes for Guidance on the SHW recognises this difference and suggests that when PFA is used in CBM, cube strength compliance should be carried out at 28 days rather than the 7 days required for CEM I only mixtures. This is provided the contractor shows from trial mixes that the 28-day strength of the PFA modified CBM compares with that of the straight CEM I mixture which meets the SHW requirements at 7 days. In addition, the Notes for Guidance provide construction advice.

Figure 1- Mixing modified GFA
(Picture courtesy of Fitzpatrick Contractors Ltd.)

Strength Compliance of CBM 3, 4 and 5 with PFA

The following table shows results from 1998 using different PFA's, CEM I's and aggregates.

MIX DESIGNATION	Proportions % by dry weight			Cube strengths (MPa) at age				
	OPC	PFA	AGG	3	7	28	56	91
CBM 3 (CEM I) - theoretical	5	-	95	-	≥10	~12	~13	~14
CBM 3 (CEM I/PFA) - actual	3	12	85	5	6.5	15	19	22
CBM 4 (CEM I) - theoretical	6	-	94	-	≥15	~18	~20	~21
CBM 5 (CEM I) - theoretical	7	-	93	-	≥20	~24	~26	~28
CBM 4, 5 (CEM I/PFA) - actual	3.5	7.5	89	-	16	24	-	-

The strength developments shown for CBM 3, 4 and 5 (CEM I) illustrate the theoretical minimum cases. From the actual strength data for the PFA modified CBM it is clear the CBM 3, 4 and 5 strengths at achieved with ease at 28 days.
The table illustrates that significant PC (CEM I) and aggregate savings are possible through the use of PFA in CBM, thus realising important environmental and energy benefits.
On the basis that PFA is similar in price to aggregate, it’s use realises typical cost savings of 10%/m3.

Figure 2 - Paving PFA modified CBM 4 roadbase
(Picture courtesy of Fitzpatrick Contractors Ltd.)

Acknowledgements
UKQAA would like to thank **Groundwork** and Fitzpatrick Contractors Ltd. for their assistance in this project.

(In general usage the term 'fly ash' is used for pulverised coal ash but it can also cover ash from burning other materials. Such 'fly ash' may have significantly differing properties and may not offer the same advantages as ash from burning pulverised coal. UKQAA datasheets only refer to pfa / fly ash produced from the burning of coal in power stations.)

V2Apr2001

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TECHNICAL DATASHEET NO. 6.5

LFA for Capping and Sub-Base

Introduction:
Lime Fly Ash (LFA) is lime treated PFA. It is a slow setting and hardening mixture. This datasheet describes the results of laboratory testing on mixtures of LFA using run-of-station conditioned (wet) PFA and quick lime (CaO). The purpose of the note is to illustrate the potential of LFA for capping and sub-base. Results for CFA (cement treated PFA) are included for comparative purposes.

Compressive strength*: (MPa)*

Sealed specimens	LFA with 2.5% CaO	LFA with 5% CaO	CFA with 7% PC	CFA with 9% PC
7 days	1.5	1.8	3.0	5.0
28 days	---	---	4.0	8.0
35 days	4.0	4.0	---	---
28 days + 7 days in water	3.3	3.3	---	---
91 days	5.0	7.3	6.0	9.0

i) Standard Proctor Optimum Moisture Content (OMC) for mixtures ~ 21%. Typical specimen wet density ~1600 Kg/m^3.

ii) Mixture percentages are based on dry weight. Thus 2.5% CaO ~ 33 kg/m^3.

iii) Strength results are for 1:1 cylinders and can be considered equivalent to cubes.

iv) Specimens were cured at 20C and sealed to prevent evaporation.

v) The results at 28 + 7 days designate 28 days curing by sealing followed by 7 days in water.

Discussion of results: The results show the advantage of OPC over CaO at 7 days but illustrate the superiority of CaO at 91 days. The above results suggest that 5% CaO ~ 8% OPC.

- Soaked strengths for LFA are about 80% of unsoaked strengths.
- The cube strength requirement for cement bound sub-base (CBM 1) for a flexible pavement is 4.5MPa at 7 days. Projected to 91 days yields an equivalent strength requirement of ~ 7 MPa. LFA with 5% CaO satisfies this 91 day projection
- The typical UK requirement for capping is a soaked CBR of 15%. The above results indicate that since the LFA mixture with 2.5% CaO is almost of CBM 1 quality and that soaked strengths are good, it should satisfy capping strength requirements.
- The above results are typical for LFA mixtures. However there will be some variation in strength for PFA and lime from different sources.

Gotham by-pass, Notts. Levelling LFA

Construction advice for LFA

- It should be noted that below 5 degrees C, the reaction between lime and PFA virtually ceases. This is generally not a problem with capping but LFA sub-base work should be limited to April to September unless the roadbase is laid & surfaced before the first frosts.
- Soft burnt fine grade quick lime or hydrated lime should be used for LFA
- LFA is best produced in pug-mill mixers, laid 'high' & trimmed by 'tracked' blades, and compacted by pneumatic-tyred roller.
- At OMC, LFA will support traffic immediately. Surface disturbance may/will occur but can be rectified with wetting, shaping & rolling 3 days & probably longer after laying.
- For best results, LFA should be overlain within 4 hours by the next layer. If this is not possible, LFA should be sealed or kept moist to prevent drying out.

Gotham by-pass, Notts. Compacting CFA.

Acknowledgements
UKQAA would like to thank **Groundwork** for their assistance in this project.

(In general usage the term ‘fly ash’ is used for pulverized coal ash but it can also cover ash from burning other materials, e.g. incinerator ash. Such 'fly ash' may have significantly differing properties and may not offer the same advantages as ash from burning pulverized coal. UKQAA datasheets only refer to PFA / fly ash produced from the burning of coal in power stations.)

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TECHNICAL DATA SHEET E

PFA AND THE ENVIRONMENT

Sustainability and the Environmental aspects

Sustainability is defined as the ability to leave sufficient resources for future generations and yet satisfy the needs of the current generation. The current generation needs electricity and one of the most abundant sources of fuel for generating electricity is coal. There are many hundreds of years of coal supplies throughout the world making it an invaluable and relatively sustainable resource. As a by product of burning the coal, ash is produced.

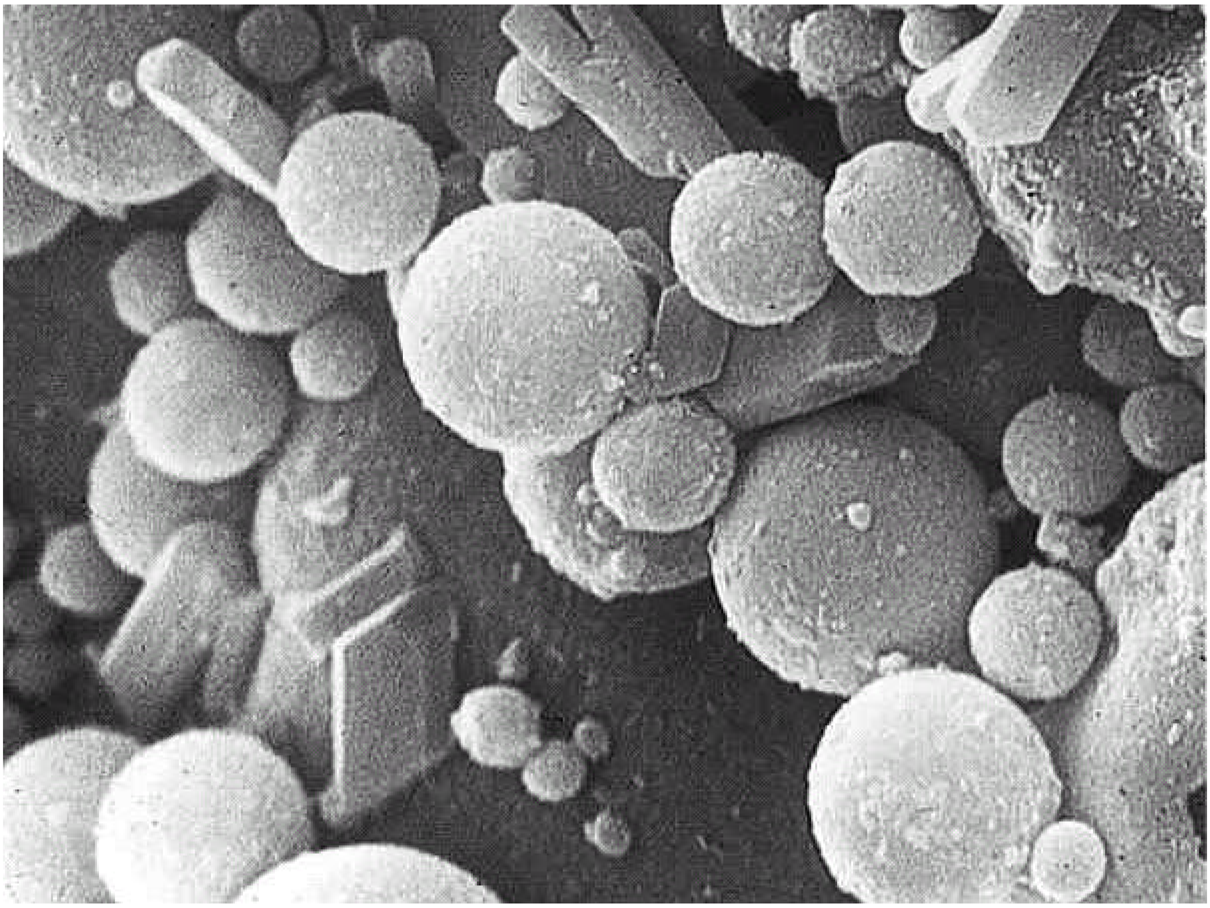
There are two main types of coal ash; furnace bottom ash (FBA) and pulverised fuel ash (PFA), also known as fly ash. These coal ashes are valuable sustainable resources in themselves.

Furnace Bottom Ash

Approximately 20% of all the ash produced from burning coal is FBA. This valuable material is mainly all used in the manufacture of building blocks. These blocks are widely used in construction for housing, office accommodation, etc. Environmentally the use of FBA reduces the demand from the construction industry on primary aggregate sources, e.g. aggregates extracted from the ground or dredged from the sea - such as gravel, limestone, sand, etc. Alternatively FBA can be used as a sub base material for road construction.

Pulverised Fuel Ash

PFA is a fine alumino-silicate material which consists of spherical particles. There are many uses for PFA as follows:



As a partial replacement for cement within concrete mixes.

- PFA reacts with lime which is formed as a by-product of the reaction of cement with water. This reaction is known as a pozzolanic reaction which enhances the strength and durability of the concrete. See UKQAA Technical Datasheet "Pulverised Fuel Ash for Concrete".
- Some forms of PFA reduce the water requirement of concrete. The more water there is in concrete the lower the strength and durability of the resulting structure.
- Cement production is an energy intensive process and the partial replacement of cement by PFA reduces the overall energy needs and the environmental consequences. To produce one tonne of Portland cement typically requires 2.81 tonnes of coal. If 30% of the cement content is replaced by PFA this reduces the coal required to 1.99 tonnes with an additional benefit of a 30% reduction in CO_2 produced.
- PFA can be used as a hydraulic binder for recycled aggregates when combined with cement and/or lime. This has been successfully used in fly ash bound materials. See Technical Datasheet on FABM's for further information.
- The pozzolanic reaction continues for many years, in the presence of water, which leads to very strong durable concrete. Volcanic ash, which is virtually identical to PFA, was used by the Romans to produce a form of concrete which has proved to be highly durable, e.g. the Pantheon in Rome. PFA imparts the same properties to modern concretes.
- Highly durable structures last longer reducing the needs of rebuilding and refurbishment. This reduces the whole life costs, energy needs and environmental impact.

As a structural fill material.

- Compacted PFA is used as a lightweight, low permeability fill material to form stable embankments which can be used in many types of construction. See UKQAA Technical Datasheet "Pulverised Fuel Ash for Fill". Because of the nature of weathered PFA there is virtually no leaching of toxic compounds or permeation of water through this type of fill. This protects water courses and rivers from any contamination. With prudent management, any potential toxic effects arising from the existing patterns of production, handling, storage and use of fresh PFA can be controlled.

- The soluble fraction of fresh PFA consists mainly of calcium, potassium and sodium sulphates together with low concentrations of other elements including boron. Most plants have a relatively low tolerance to soluble forms of boron, It is known that in addition to a high level of non-specific salts, e.g. salinity, the run off from piles of unweathered PFA temporarily exposed to rainfall may also be high enough in boron to give rise to phytotoxic effects in sensitive plant species.
- Contaminated land can be reclaimed. By forming a barrier layer of PFA over the ground prior to construction the contaminates can be safely locked in. As all the contaminated material does not have to be removed the resulting reduction in transport has both financial and environmental benefits.
- PFA is able to quickly support the growth of vegetation with the application of soil and/or suitable fertilisers. Some landscaped ash fields have subsequently been designated as sites of special scientific interest because of the wide variety of flora and fauna that have developed over the years.

As a grouting material.
PFA in combination with lime or cement can be used to form a fluid grout used to strengthen weak ground. This allows unsuitable and weak ground to be used for construction needs. This puts less pressure on green field sites and allows ‘brown’ sites to be successfully redeveloped. See UKQAA Technical Datasheet "Pulverised Fuel Ash for Grouts".

As a manufactured aggregate

- PFA can be made into an artificial aggregate which is a strong, lightweight, fire resisting, easy to use material. See UKQAA Technical Datasheet "Manufactured Aggregates".
- It can be used in concrete to reduce the dead load of structures thereby reducing the needs for massive foundations, and allowing taller structures, larger spans, etc. Overall this reduces the need for primary aggregates and cement with the associated environmental benefits.
- Lightweight PFA aggregate has better insulation properties than primary aggregates reducing heat losses from buildings and improving energy efficiency.
- Lightweight PFA aggregate makes an excellent drainage, filter and horticultural medium.

As a fine aggregate.
PFA can be used as a fine aggregate in road sub-bases reducing the need for primary aggregates.
Since it is lightweight and thermally efficient, building blocks use PFA as a fine aggregate again reducing the need for primary aggregates.
It can be used to make coarse unusable fine aggregates suitable for a number of applications, e.g. concrete.

General considerations
The impact on the environment of obtaining primary aggregates is increasingly unacceptable. PFA and FBA as by-products from the generation of electricity are useful resources in their own rights. Their use in a wide variety of construction applications reduces the demands on primary aggregates. Full utilisation of ashes from power stations could have significant environmental benefits and reduce the needs for primary aggregate extraction. Additionally the strength enhancing properties of PFA are able to reduce the overall energy need in the manufacture of concrete - an invaluable construction material.

The United Kingdom Quality Ash Association
The UKQAA is actively promoting the use and development of coal ash in many fields. Research is being directed towards both existing and new applications. We believe power station coal ash is a valuable resource which should be fully utilised to reduce the need for primary aggregates and the overall energy usage. In addition PFA improves structure durability and offers significant benefits over more traditional materials when whole life costing techniques are employed.

(Pulverised Fuel Ash (PFA) is also known as 'fly ash' in European Standards and in many countries. Fly ash can refer to ashes produced from furnaces other than those from coal burning power generation. Such fly ash may have significantly differing properties and may not offer the same advantages as PFA. The UKQAA datasheets only refer to PFA/fly ash produced from the burning of hard bituminous coal within power station furnaces.)

CEN TC 227

Date: 2000-08

TC 227 WI 190

CEN TC 227

Secretariat: DIN

Unbound and hydraulically bound mixtures — Part 3: Fly ash bound mixtures — Definitions, composition, classification

Ungebundene und hydraulisch gebundene Gemische — Teil 3: Flugaschegebundene Gemische — Definitionen, Zusammensetzung, Einstufung

Mélanges traités et non traités aux liants hydrauliques — Partie 3 : Mélanges traités à la cendre volante — Définitions, composition, classification

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Contents

Foreword 3
1 Scope 3
2 Normative references 3
3 Terms and definitions 4
4 Symbols and abbreviation 4
5 Constituents 5
6 Fly ash bound mixtures 5
7 Laboratory performance classification 7
8 Marking and labelling 10
Annex A (normative) Compacity of FABM 17
Annex B (normative) Laboratory performance classification by $R_t E$ 18
Annex C (informative) Examples of fly ash bound mixtures (FABM) for road and airfield construction using siliceous fly ash 19
Annex D (informative) Examples of fly ash bound mixtures (FABM) for road and airfield construction using calcareous fly ash 20

Foreword

This document has been prepared by CEN/TC 227, "Road materials".

This document is currently submitted to the CEN Enquiry.

According to the CEN/CENELEC Internal Regulations, the national standards organizations of the following countries are bound to implement this document: Austria, Belgium, the Czech Republic, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the United Kingdom.

1 Scope

The Standard defines "Fly Ash Bound Mixtures" (FABM) for roads (roadbase, subbase, capping and earthworks) and similar works and specifies the requirements for their constituents, composition and laboratory performance classification. In this standard, fly ash refers to siliceous or calcareous fly ash, produced from the combustion of pulverized coal in energy generating plants. The treatment of soils with fly ash is not covered by this standard, but is currently under preparation.

2 Normative references

This European Standard incorporates by dated or undated reference, provisions from other publications. These normative references are cited at the appropriate places in the text and the publications are listed hereafter. For dated references, subsequent amendments to or revisions of any of these publications apply to this European Standard only when incorporated in it by amendment or revision. For undated references the latest edition of the publication referred to applies.

EN 197-1, *Cement — Part 1: Composition, specifications and conformity criteria.*

prEN 459-1, *Building lime — Part 1: Definitions, specifications and conformity criteria.*

prEN 13242, *Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction.*

prEN 13286-1, *Unbound and hydraulically bound mixtures — Part 1: Test methods for laboratory reference density and moisture content — Introduction and general requirements.*

prEN 13286-2, *Unbound and hydraulically bound mixtures — Part 2: Test methods for laboratory reference density and moisture content — Proctor compaction.*

prEN 13286-3, *Unbound and hydraulically bound mixtures — Part 3: Test methods for laboratory reference density and moisture content — Vibrocompression with controlled parameters.*

prEN 13286-4, *Unbound and hydraulically bound mixtures — Part 4: Test methods for laboratory reference density and moisture content — Vibrating hammer.*

prEN 13286-5, *Unbound and hydraulically bound mixtures — Part 5: Test methods for laboratory reference density and moisture content — Vibrating table.*

prEN 13286-6, *Unbound and hydraulically bound mixtures — Part 6: Test methods for laboratory reference density and moisture content — Test method for sampling and sample reduction*.

prEN 13286-41, *Unbound and hydraulically bound mixtures — Part 41: Test method for the determination of the compressive strength of hydraulically bound mixtures.*

prEN 13286-42, *Unbound and hydraulically bound mixtures — Part 42: Test method for the determination of the indirect tensile strength of hydraulically bound mixtures*.

prEN 13286-43, *Unbound and hydraulically bound mixtures — Part 43: Test method for the determination of the modulus of elasticity of hydraulically bound mixtures.*

prEN (WI 00227xxx)-.., *Unbound and hydraulically bound mixtures — Part …: Methods for making test specimens.*

prEN (WI 00227139)-40, *Unbound and hydraulically bound mixtures — Part 40: Test method for the determination of the direct tensile strength of test specimens of hydraulically bound mixtures*.

prEN (WI 00227168)-47, *Unbound and hydraulically bound mixtures — Part 47: Test methods for the determination of bearing capacity — Calfornia Bearing Ratio (CBR), immediate bearing index (IBI) and linear swelling.*

prEN (WI 00227189)-2, *Unbound and hydraulically bound mixtures — Part 2: Slag bound mixtures — Definition, composition, classification.*

prEN (WI 00227191)-4, *Unbound and hydraulically bound mixtures — Part 4: Fly ash for hydraulically bound mixtures — Definitions, composition, classification*.

3 Terms and definitions

For the purposes of this European Standard, the following terms and definitions apply.

3.1
hydraulic reaction
setting and hardening in the presence of water to form stable and durable compounds

3.2
hydraulically bound mixture
mixture which sets and hardens by hydraulic reaction

3.3
fly ash bound mixture
hydraulically bound mixture where siliceous or calcareous fly ash is the essential constituent. Hardening can be controlled by additional constituents

3.4
slenderness ratio
height of the specimen divided by its diameter

4 Symbols and abbreviation

IPI Immediate Bearing Index, expressed in percent (%);

FABM fly ash bound mixture;

R_c compressive strength, expressed in MegaPascal (MPa);

R_t direct tensile strength, expressed in Mega Pascal (MPa);

R_{it} indirect tensile strength, expressed in Mega Pascal (MPa);

E modulus of elasticity, expressed in Mega Pascal (MPa);

E_c E determined in compression, expressed in Mega Pascal (MPa);

E_t E determined in direct tension, expressed in Mega Pascal (MPa);

E_{it} E determined in indirect tension, expressed in Mega Pascal (MPa);

LOI loss on ignition, expressed in percentage by mass.

5 Constituents

5.1 Fly Ash

Siliceous or calcareous fly ash complying with prEN 227407.

5.2 Lime

Quick lime [CaO] or hydrated lime [$Ca(OH)_2$] complying with EN 459-1 or other approved product.

5.3 Cement

Cement complying with EN 197-1.

5.4 Aggregate

Unless stated otherwise, the aggregate shall be selected from prEN 13242.

The requirements for the aggregate shall be specified according to the utilisation of the mixture in the structure, the type of structure and the traffic.

5.5 Gypsum

Gypsum is a hardening activator. Gypsum can be natural or artificial. The percentage of ($CaSO_4 \cdot 2\ H_2O$) shall be higher than 90 %. The maximum size shall be less than 5 mm. Unless the constituents and the mixture are well known and proven, it will be necessary to check the expansion of mixtures containing gypsum.

5.6 Granulated Blast Furnace Slag

Granulated blast furnace slag in accordance with prEN (WI 00227189)-2.

5.7 Other Constituents

Constituents, including calcium chloride and sodium carbonate, which can be used to enhance the setting and hardening of FABM.

5.8 Water

Water shall not contain components which adversely affect the hardening and the performance of FABM.

6 Fly ash bound mixtures

6.1 General

There are three types of FABM. These are shown in Table 1 and described and specified below. The type of FABM shall be specified in accordance with application and experience.

Table 1 — Types of FABM

Type	Main constituent (defined as > 50 % of the mass of the mixture)
FABM 1	Siliceous or calcareous fly ash complying with prEN (WI 00227191)-4
FABM 2	Graded aggregate complying with prEN 13242 (This type is sub-divided into three sub-categories: 0 - 14 mm, 0 - 20 mm and 0 – 31,5 mm.)
FABM 3	Aggregate complying with prEN 13242 with a maximum particle size of 6,3 mm. (This includes fine aggregate sand.)

6.1.2 The water content is selected to permit compaction on site by rolling and to optimise the mechanical performance of the mixture. It shall be determined by the Proctor test or other method in accordance with prEN 13286, Part 1 to 6 and limits set to give a workable range of water content on site compatible with the compaction and the desired mechanical performance of the mixture.

6.1.3 The laboratory performance characterization and classification shall be selected from clause 7.

6.2 FABM 1

6.2.1 FABM 1 is a hydraulically bound mixture where fly ash is the main constituent of the mixture and forms part of the binder.

6.2.2 Fly ash shall be siliceous or calcareous fly ash complying with prEN (WI 00227191)-4, except that in the case of treatment with cement, the LOI requirement may be relaxed with the agreement of the client.

6.2.3 In the case of lime activated FABM 1 containing gypsum, the proportion of gypsum shall not exceed 7 % by mass and the proportion of quick lime (CaO) shall not exceed 5 %. In the case of hydrated lime ($Ca\ OH_2$), the corresponding maximum proportion is 6 %. The gypsum shall comply with the requirements of 55. Unless the constituents and the mixture are well known and proven, the mixture will need to be checked for expansion.

6.3 FABM 2

6.3.1 FABM 2 is a hydraulically bound granular mixture where fly ash forms part of the binder.

6.3.2 The aggregate shall comply with prEN 13242. The intrinsic characteristics; resistance to fragmentation, fines, harmful constituents and percentage of crushed particles, shall be specified according to the use of the mixture.

6.3.3 The grading of the mixture shall comply with either the class 1 or class 2 envelope as follows:

Table 2 — Gradings of the mixture

Type of mixture	Grading	Mixture using siliceous fly ash	Mixture using calcareous fly ash
FABM 2A	0 to 14 mm	Figure 1	Figure 2
FABM 2B	0 to 20 mm	Figure 3	Figure 4
FABM 2C	0 to 31,5 mm	Figure 5	Figure 6

6.3.4 The minimum compacity of the mixture shall be 0,80 as calculated in accordance with annex A.

6.4 FABM 3

6.4.1 FABM 3 is a hydraulically bound mixture, with a maximum particle size of 6,3 mm, where fly ash forms part of the binder.

6.4.2 There is no requirement for grading of the aggregate.

6.4.3 In order to facilitate site compaction and trafficking, the IPI-value of the mixture determined in accordance with prEN (WI 00227168)-47 shall be not less than 40. Mixture with an IPI-value between 25 and 40 may be used with care. The addition of another aggregate may be necessary to achieve the IPI-value.

6.5 Examples of FABM

Annexes C and D give examples of FABM 1, 2 and 3.

NOTE The examples are not exhaustive, nor the proportions intended to be restrictive, but illustrate the current use in Europe.

7 Laboratory performance classification

7.1 General

There are two methods of characterising the laboratory performance of fly ash bound mixtures (FABM):

— by compressive strength (R_c);

— by the combination (R_tE) of tensile strength (R_t) and modulus of elasticity (E).

No correlation is intended nor shall be assumed between the two methods of characterisation. The pavement designer shall select the method.

NOTE The choice of method depends on design philosophy, utilisation and experience. The R_tE method is particularly applicable where pavement design is formulated using analytical methods.

7.2 Classification by R_c

FABM is classified by compressive strength (R_c) determined in accordance with prEN 13286-41 carried out on specimens manufactured in accordance with one of the methods from prEN 13286-6 and cured at 20 °C without evaporation resulting in a loss of bulk density of more than 2 % (deemed normal curing).

Ten classes of R_c are covered in this European standard and are shown below and in Table 3:

C2/1,5, C4/3, C8/6, C12/9, C 16/12, C20/15, C24/18, C28/21, C32/24, C36/27

C designating compressive strength and the first number after C designating the minimum standard strength in MPa of the class determined on cylinders with a slenderness ratio of 1 or cubes, and the second number relating to cylinders with a slenderness ratio of 2.

NOTE 1 Strength can also be determined from cylinders with slenderness ratios other than 1 and 2. The corresponding strength for cylinders with ratios other than 1 and 2 shall be established before use by correlation with cylinders with ratios of either 1 or 2.

The age of classification shall be 360 days or earlier, typically 90 days for FABM activated by lime alone and 28 days for FABM containing cement.

NOTE 2 The 360 day value may be estimated from early age results at 7 days, 28 days, 60 days or 90 days, employing normal curing at 20 °C or elevated curing at 40 °C. In these cases, the producer shall provide evidence of the strength development and method of curing over 360 days and report this in the labelling. In the case of FABM activated by lime alone, there is tentative evidence that the following relationships may apply:

— R_c (360 days, normal curing) = 1,5 R_c (90 days, normal curing);

— R_c (360 days, normal curing) = R_c (28 days, 40 °C without evaporation).

In the case of FABM containing cement, there is tentative evidence that the following relationship applies:

— R_c (360 days, normal curing) = 1,5 R_c (28 days, normal curing).

For characterisation or mixture design testing in the laboratory, R_c shall be the average result from at least three specimens. If one value varies by more than 20 % of the average, it shall be discarded and R_c taken as the average of the other values.

The pavement designer shall select the required R_c class from table 3 and the method of specimen manufacture from prEN 13286-6. FABM shall comply with the minimum strength of that class.

NOTE 3 The pavement designer should be aware that the permitted methods of specimen manufacture realise different specimen shapes and density, and thus for the same mixture, different strengths. It is important that the pavement designer, on the basic of experience and utilisation, specifies both the strength class and method of specimen manufacture.

Table 3 — R_c classification

R_c Class	R_c in MPa for cylinders of slenderness ratio 1[a] and cubes	R_c in MPa for cylinders of slenderness ratio 2[a]
C 2 / 1,5	2	1,5
C 4 / 3	4	3
C 8 / 6	8	6
C 12 / 9	12	9
C 16 / 12	16	12
C 20 / 15	20	15
C 24 / 18	24	18
C 28 / 21	28	21
C 32 / 24	32	24
C 36 / 27	36	27

[a] If cylinders with slenderness ratios other than 1 and 2 are used, then the correlation with cylinders of either slenderness ratio 1 or 2 shall be established before use.

7.3 Classification by R_tE

FABM is classified by tensile strength (R_t) and modulus of elasticity (E), designated R_tE, determined on specimens cured at 20 °C without evaporation resulting in a loss of bulk density of more than 2 % (deemed normal curing).

Six classes of R_tE are covered in this European Standard according to the position of the couple R_t and E on figure 4. The classes are designated as follows:

$T > 47$, $T$34/47, $T$25/34, $T$20/25, $T$15/20, $T < 15$

T designating tensile testing and the number after T representing the theoretical range of thickness of layer required by a FABM falling in that class when analysed in accordance with the attached annex B.

R_t and E shall be established using one of the following methods. They are equivalent.

7.3.1 Method R_tE_t by direct tensile testing

R_t determined in accordance with prEN (WI 00227139)-40 and E determined in direct tension (E_t) in accordance with prEN 13286-43. R_t and E_t shall be determined on specimens manufactured using vibrocompression in accordance with prEN 13286-3.

7.3.2 Method R_tE_{it} by indirect tensile testing

R_t derived from R_{it} determined in accordance with prEN 13286-42 using the relationship $R_t = 0{,}8\,R_{it}$, and E determined in indirect tension (E_{it}) in accordance with prEN 13286-43. R_{it} and E_{it} shall be determined on specimens manufactured using:

— either vibrocompression for both in accordance with prEN 13286-3; or

— proctor compaction for both in accordance with prEN 13286-2; or

— vibrating hammer for both in accordance with prEN 13286-4; or

— static compaction for both in accordance with prEN 13286-5.

7.3.3 Method R_tE_c by indirect tensile and compression testing

R_t derived from R_{it} determined in accordance with prEN 13286-42 using the relationship R_t = 0,8 R_{it}, and E determined in compression (E_c) in accordance with prEN 13286-43. R_{it} and E_c shall be determined on specimens manufactured using:

— either vibrocompression for both in accordance with prEN 13286-3; or

— proctor compaction for both in accordance with prEN 13286-2; or

— vibrating hammer for both in accordance with prEN 13286-4; or

— static compaction for both in accordance with prEN 13286-5.

The age of classification shall be 360 days or earlier, typically 90 days for FABM activated by lime alone and 28 days for FABM containing cement.

NOTE 1 The 360 days values of R_t and E may be estimated from early age results e.g.3 days, 7 days, 28 days, 60 days or 90 days, employing either normal or high temperature curing. In these cases, the producer shall provide evidence on the strength and stiffness development and method of curing over 360 days.

In the case of FABM mixtures activated by lime alone, there is tentative evidence that the following relationships apply:

— R_t (360 days, normal curing) = 1,5 R_t (90 days, normal curing);

— E (360 days, normal curing) = 1,3 E (90 days, normal curing).

In the case of FABM containing cement, there is tentative evidence that the following relationship apply:

— R_t (360 days, normal curing) = 1,5 R_t (28 days, normal curing);

— E (360 days, normal curing) = 1,4 E (28 days, normal curing).

For characterisation or mixture design testing in the laboratory, R_t and E shall be the average result from at least three specimens. If one value varies by more than 20 % of the average, it shall be discarded and R_t or E taken as the average of the other values.

The pavement designer shall select the R_tE class from Figure 4 and the method of specimen manufacture from prEN (WI 00227xxx)-. The FABM shall comply with the lower boundary of the class selected.

NOTE 2 prEN (WI 00227xxx)- covers the manufacture of specimens using either proctor compactive effort, vibrating hammer compaction vibrocompression or static compression. The pavement designer should be aware that each method of manufacture realises a different state of compaction, and thus for the same mixture, different strengths and stiffnesses. It is important that the pavement designer, on the basis of experience and utilisation, specifies the method of specimen manufacture.

8 Marking and labelling

The product shall be identified by:

a) the type of FABM;

b) the constituents, their characteristics and properties;

c) the method of manufacture for laboratory performance specimens;

d) the density and water content of specimens;

e) the type of laboratory performance characterisation and its class;

f) the curing conditions for the specimens and age of testing;

g) origin;

h) name of producer/supplier.

Table 4 — Particle size distribution

Particle size distribution			
Sieve	**Percentage passing by mass**		
mm	minimum	maximum/ class1	maximum/ class2
25	100		
14	84	100	
10	73	97	100
6,3	59	81	87
4	49	67	74
2	35	51	57
0,5	20	32	35
0,2	14	24	27
0,08	10	20	21

(missed)

Key
1 Class 1
2 Class 2

Figure 1 — Grading curves of mixtures with siliceous fly ash, binder included, FABM 2A (*D* = 0 / 14 mm)

Table 5 — Particle size distribution

Particle size distribution			
Sieve	**Percentage passing by mass**		
mm	minimum	maximum/ class1	maximum/ class2
25	100		
14	85	100	100
10	68	90	97
6,3	50	72	84
4	38	60	71
2	26	46	56
0,5	13	27	32
0,2	9	19	21
0,08	5	11	12

(missed)

Key
1 Class 1
2 Class 2

Figure 2 — Grading curves of mixtures with calcareous fly ash, binder included, FABM 2A (*D* = 0 / 14 mm)

Table 6 — Particle size distribution

Particle size distribution			
Sieve	**Percentage passing by mass**		
mm	minimum	maximum/ class1	maximum/ class2
31,5	100		
20	85	100	100
10	60	83	88
6,3	47	69	75
4	39	59	66
2	29	47	53
0,5	18	30	34
0,2	13	23	26
0,08	9	19	21

(missed)

Key
1 Class 1
2 Class 2

Figure 3 — Grading curves of mixtures with siliceous fly ash, binder included, FABM 2B (*D* = 0 / 20 mm)

Table 7 — Particle size distribution

Particle size distribution			
Sieve	**Percentage passing by mass**		
mm	minimum	maximum/ class1	maximum/ class2
31,5	100		
20	85	100	100
10	55	80	88
6,3	42	66	74
4	32	56	66
2	23	43	54
0,5	11	26	31
0,2	7	17	21
0,08	4	10	12

(missed)

Key
1 Class 1
2 Class 2

Figure 4 — Grading curves of mixtures with calcareous fly ash, binder included, FABM 2B (*D* = 0 / 20 mm)

Table 8 — Particle size distribution

Particle size distribution			
Sieve	**Percentage passing by mass**		
mm	minimum	maximum/ class1	maximum/ class2
40	100		
31,5	85	94	100
20	70	80	90
10	47	60	73
6,3	37	49	61
4	28	40	52
2	20	30	40
0,5	10	18	25
0,2	6	11	16

(missed)

Key
1 Class 1
2 Class 2

Figure 5 — Grading curves of mixtures with siliceous fly ash, binder included, FABM 2C (*D* = 0 / 31,5 mm)

Table 9 — Particle size distribution

Particle size distribution			
Sieve	**Percentage passing by mass**		
mm	minimum	maximum/ class1	maximum/ class2
31,5	85		
20	63	88	76
10	42	67	55
6,3	34	57	45
4	28	51	39
2	22	42	31
0,5	12	27	19
0,2	8	19	12
0,08	6	12	8

(missed)

Key
1 Class 1
2 Class 2

Figure 6 — Grading curves of mixtures with calcareous fly ash, binder included, FABM 2C (*D* = 0 / 31,5 mm)

(missed)

Figure 7 — Classification by R_tE

Annex A
(normative)

Compacity of FABM

The compacity before setting of a FABM is defined as the value of the ratio:

absolute volume of solid/apparent volume of the mixture

This can be calculated by the following formula:

$C = \gamma m/100 \times (a/\gamma A + b/\gamma B + d/\gamma D \ldots)$

where

C is the compacity;

γm is the apparent volumetric mass of the dry mixture;

γA is the real volumetric mass of the constituent A;

γB is the real volumetric mass of the constituent B;

γD is the real volumetric mass of the constituent D;

a is the constituent A content in mass related to the mixture, expressed in percent (%);

b is the constituent B content in mass related to the mixture, expressed in percent (%);

d is the constituent D content in mass related to the mixture, expressed in percent (%).

Annex B
(normative)

Laboratory performance classification by R_tE

In a road structure, a layer works in flexion. Under a specified condition, the stress of the layer depends on the modulus of elasticity E of the materials and the layer fails when the tensile stress σ at the bottom of the layer exceeds the tensile strength R_t of the material. The essential mechanical characteristics of the materials are then the modulus of elasticity E and the strength of rupture in tension R_t.

In order to compare the mechanical performance of two materials, it is necessary to combine the two values R and R_t into one value as follows:

Consider a one layer structure made with a material with an elastic modulus E and a tensile strength R_t. That layer lays on a subgrade with an elastic modulus of 100 Mpa and is submitted to a load represented by two circular surfaces with a radius of 12,5 cm and a pressure of 12,5 MPa. That correspond to an axle load of 13 t.

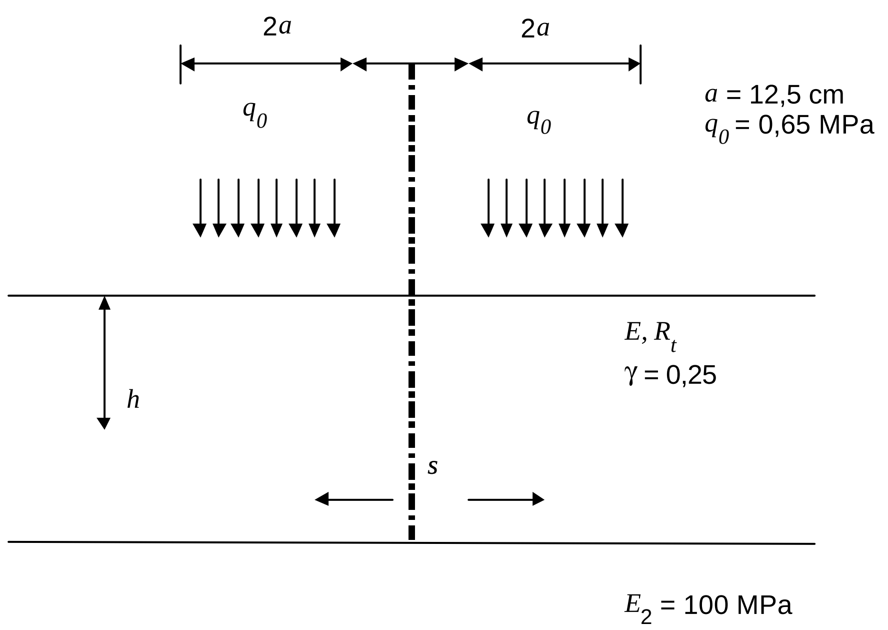

Figure B.1

According to the value of E and R_t of the material, a theoretical calculation gives the thickness of the layer. The lines that limit the classifications given on the Figure 7 give the equivalent of the layers according to the material used.

The classification is made according to six classes which are limited by thickness in cms of: 15, 20, 25, 35, 47. The class T20/25 for example corresponds to a theoretical thickness less than 25 cm but greater than 20.

Annex C
(informative)

Examples of fly ash bound mixtures (FABM) for road and airfield construction using siliceous fly ash

Ref	Type	Examples	Typical proportions as a percentage of dry mass %						Typical water content %	Age[a] of performance testing days
			Siliceous Fly Ash	Lime[b]	Cement	Sand	Coarse aggregate	Other Material		
1	FABM1	Fly Ash / Lime	93 to 97	3 to 7	—	—	—	—	15 to 25	90
2		Fly Ash / Lime / Gypsum	91	4	—	—	—	5 % gypsum	15 to 25	90
3		Fly Ash / Cement	90 to 95	—	5 to 10	—	—	—	15 to 25	28
4	FABM2	Fly Ash / Lime / Granular Material	4 to 13	1 to 3	—	30 to 40	50 to 55	—	6 to 8	90
5		Fly Ash / Cement / Granular Material	3 to 6	—	1 to 3	40 to 45	50 to 55	—	6 to 8	28
6		Fly Ash / GBS[c] / Granular Material	5 to 7	0 to 2	—	30 to 40	50 to 55	5to7 %GBS[c]	6 to 8	90
7	FABM3	Fly Ash / Lime / Sand	9 to 12	2 to 4	—	84 to 89	—	—	~10	90
8		Fly Ash / Cement / Sand	6 to 8	—	2 to 4	88 to 92	—	—	~10	28

[a] Earlier age testing is permissible subject to data and experience.

[b] Lime means CaO or $Ca(OH)_2$, and may be supplied preblended with dry fly ash.

[c] Granulated blast furnace slag.

Annex D
(informative)

Examples of fly ash bound mixtures (FABM) for road and airfield construction using calcareous fly ash

Ref	Type	Examples	Typical proportions as a percentage of dry mass %					Typical water content %	Age[a] of performance testing days
			Calcareous Fly Ash	Cement	Sand	Coarse Aggregate	Other Material		
1	**FABM1**	Fly Ash / Cement	80 to 95	5 to 20	—	—	—	15 to 30	28
2	**FABM2**	Fly Ash / Granular Material	3 to 6	—	—	94 to 97	—	5 to 7	28
3		Fly Ash / Cement / Granular material	3 to 16	1 to 4	—	80 to 96	—	5 to 7	28
4	**FABM3**	Fly Ash / Sand	4 to 8	—	92 to 96	—	—	~10	28
5		Fly Ash / GBS[b] / Sand	2 to 4	—	92 to 96	—	2 to 4 % GBS[b]	5 to 7	28
6		Fly Ash / Cement / GBS[b] / Sand	1 to 3	1 to 2	92 to 96	—	1 to 3 % GBS[b]	5 to 7	28

[a] Earlier age testing is permissible subject to data and experience.

[b] Granulated blast furnace slag.

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Unbound and hydraulically bound mixtures — Part 4: Fly ash for hydraulically bound mixtures — Definitions, composition, classification

Ungebundene und hydraulisch gebundene Gemische — Teil 4: Flugasche für hydraulisch gebundene Gemische — Definitionen, Zusammensetzung, Einstufung

Mélanges traités et non traités aux liants hydrauliques — Partie 4 : Cendre volante pour mélanges à base de liant hydraulique — Définitions, composition, classification

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Contents

1 Scope ... 3
2 Normative references ... 3
3 Terms and definitions ... 4
4 Symbols and abbreviations ... 4
5 Requirements for siliceous fly ash ... 4
6 Requirements for calcareous fly ash ... 5
7 Marking and labelling ... 6

Foreword

This document has been prepared by CEN/TC 227, "Road materials".

This document is currently submitted to the CEN Enquiry.

According to the CEN/CENELEC Internal Regulations, the national standards organizations of the following countries are bound to implement this document: Austria, Belgium, the Czech Republic, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the United Kingdom.

1 Scope

This European Standard specifies fly ash used in hydraulically bound mixtures for roadbase, subbase, capping and similar works. The standard applies to fly ash produced by the combustion of pulverized coal in energy generating plants.

There are two types of fly ash depending on the type of coal burned and/or the desulphurisation process.

One type behaves pozzolanically and the dominant chemical constituent are SiO_2 and Al_2O_3; this is called alumino-silicate or siliceous fly ash.

The other type behaves hydraulically and the dominant chemical constituents are CaO, SiO_2 and Al_2O_3; this is called sulpho-calcitic or calcareous fly ash.

2 Normative references

This European Standard incorporates by dated or undated reference, provisions from other publications. These normative references are cited at the appropriate places in the text and the publications are listed hereafter. For dated references, subsequent amendments to or revisions of any of these publications apply to this European Standard only when incorporated in it by amendment or revision. For undated references the latest edition of the publication referred to applies.

EN 196-3, *Methods of testing cement — Part 3: Determination of setting time and soundness*.

EN 451-1, *Method of testing fly ash — Part 1: Determination of free calcium oxide.*

EN 451-2, *Method of testing fly ash — Part 2: Determination of fineness by wet sieving*.

prEN (WI 00227190)-3, *Unbound and hydraulically bound mixtures — Part 3: Fly ash bound mixtures — Definitions, composition, classification*.

EN 197-1, *Cement — Part 1: Composition, specifications and conformity criteria*.

EN 196-7, *Methods of testing cement — Part 7: Determination of strength.*

prEN 13286-6, *Unbound and hydraulically bound mixtures — Part 6: Test methods for laboratory reference density and moisture content* - *Test methods for sampling and sample reduction.*

3 Terms and definitions

For the purposes of this European Standard, the following terms and definitions apply.

3.1
siliceous fly ash
fine powder produced by the combustion of pulverised coal in energy generating plants and captured by mechanical or electrostatic precipitators

The essentiel chemical components are silicates, aluminates and iron oxides, expressed as SiO_2, Al_2O_3 and Fe_2O_3. The fly ash has pozzolanic properties.

It can be stored, supplied and used either in a wet or dry condition.

3.2
calcareous fly ash
fine powder produced by the combustion of pulverised coal in energy generating plants and captured by mechanical or electrostatic precipitators

The essential chemical components are silicates, aluminates and calciumoxyde, expressed as S_iO_2, Al_2O_3 and CaO. The fly ash has hydraulic and pozzolanic properties.

It shall be stored in a dry condition.

3.3
pozzonalic material
material which sets and hardens with lime [$Ca(OH)_2$ or CaO] in the presence of water to form stable and durable compounds

3.4
hydraulic material
material which sets and hardens in the presence of water, to form stable and durable compounds

3.5
dry fly ash
contains less than 1 % water by dry weight

4 Symbols and abbreviations

LOI loss on ignition, expressed in percentage by mass (%).

5 Requirements for siliceous fly ash

5.1 Sampling

For dry fly ash, samples are taken and prepared in the standard EN 196-7. For wet fly ash, samples are taken and prepared as described in the standard prEN 13286-6.

5.2 Particle size

The grading shall conform with Table 1.

Sieving shall be carried out in accordance with EN 451-2.

Table 1 — Grading

Sieve	Percentage passing by mass
90 µm	≥ 70
45 µm	≥ 40

5.3 Chemical composition

Expressed as a percentage by mass of the dry product which is obtained by drying a laboratory sample in a well ventilated oven at (105 ± 5) °C to constant weight, and cooled in a dry atmosphere.

5.3.1 Loss on ignition

The loss on ignition (LOI) measured in accordance with EN196-2, but using an ignition time of 1 h, or equivalent method shall not exceed 10.0 % by mass.

NOTE The purpose of this requirement is to limit the residue of unburned carbon in fly ash. It is sufficient, therefore, to show through direct measurement of unburned carbon residue, that it is less than the value specified above.

5.3.2 Sulphate content

The sulphate content, expressed as total SO_3 (EN196-2) shall not exceed 4,0 % by mass.

5.3.3 Free calcium oxide content

The free calcium oxide content, measured in accordance with EN 451-1, shall not exceed 1,0 % by mass. If this requirement is not met, soundness shall be measured according to EN 196-3 and the expansion shall not exceed 10 mm with a 50 : 50 blend of fly ash and cement.

5.4 Water content

Dry siliceous fly ash shall contain not more than 1,0 % by mass of water. Siliceous fly ash can be stored, used and supplied either in a wet or dry condition.

5.5 Pozzolanic activity

If required on national basis, the pozzolanic activity of the siliceous fly ash shall be declared by the supplier.

6 Requirements for calcareous fly ash

6.1 Sampling

Samples are taken and prepared as described in the standard EN 196-7.

6.2 Particle size

The grading shall conform with Table 2. Sieving shall be carried out in accordance with EN 451-2.

Table 2 — Grading

Sieve	Percentage passing by mass
315 µm	≥ 95
90 µm	≥ 70

6.3 Soundness

The expansion of calcareous fly ash shall be less than 10 mm. When tested in accordance with EN 196-3 using a mixture of 30 % by mass of ground fly ash and 70 % by mass of reference cement.

6.4 Reactive CaO

The total value of reactive CaO determined in accordance with EN 197-1 shall not be less than 5 % by mass.

6.5 Water content

Dry calcareous fly ash shall contain not more than 1% by mass of water. Calcareous fly ash shall be stored and supplied in a dry condition.

6.6 Hydraulic activity

If required on a national basis, the hydraulic activity of the calcareous fly ash shall be declared by the supplier.

7 Marking and labelling

All deliveries between the origin and the final use are to be labelled with the following statements:

a) the type of fly ash in accordance with this standard;

b) the origin;

c) the producer.