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Long-term stability of landfilled coal combustion by-products

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Many of the by-products from coal combustion and flue gas desulfurization are cementitious, which suggests utilization in some settings replacing conventional cements. Information on the long-term stability of these materials in Nature can be obtained from studies of landfilled by-products. Five coal combustion by-products (CCBs) landfilled at four sites in the USA were characterized by X-ray diffraction. Where moisture was available during or after disposal, the materials were changed chemically, physically and mineralogically over time, in processes analogous to diagenesis of buried sediments. At three of the sites, initially formed crystalline-phase assemblages were transformed into an assemblage dominated by ettringite and thaumasite. At one site where a high-sodium by-product was landfilled, an assemblage of Na-rich phases, including a zeolite and a zeolite-related nosean-hauyne phase, as well as tobermorite, was observed. This assemblage is unique and previously unobserved in CCBs. Diagenesis associated with many of these CCBs reduced strength and increased permeability after only a few years in the natural environment. The characteristics of the altered by-products resemble those of soils more than concrete. Initially promising 7 or 28 day laboratory tests of strength and permeability may not be characteristic of these materials on exposure to the environment. Blending of CCBs with fly ash to increase the proportion of cementitious C-S-H, and controlling subsequent moisture additions, could minimize deleterious by-product diagenesis. © *1997 Elsevier Science Ltd.*

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Effective and appropriate utilization of coal combustion by-products (CCBs) requires that the properties observed over conventional testing periods (e.g. 28 days) are representative of the product's useful lifetime. Studies of the behaviour of landfilled CCBs can provide insights into the long-term stability of these materials when they are utilized in settings where they come in contact with soils and moisture, e.g. in civil engineering and construction applications, manufactured aggregates etc.

This paper summarizes results from two studies of CCBs placed in landfills. All of the by-products studied are cementitious, i.e. when moisture is added (e.g. for conditioning), strength-producing hydration reactions cause the materials to harden[1–3]. This consolidation is clearly an advantage, compared with unconsolidated landfilled material, because moisture infiltration is reduced and the material may maintain its physical integrity. The question addressed here concerns the long-term stability of these hardened materials in the geochemical environment of disposal. The materials discussed in this paper are broadly representative of cementitious CCBs, which include high-calcium fly ash, dry-process flue gas desulfurization (FGD) by-products and clean coal technology (CCT) by-products (fluidized bed combustion (FBC) and sorbent injection by-products that utilize lime or limestone for scrubbing SO_2).

In the first study, CCT by-products were placed in test cells at three sites and monitored at times varying from 3 months to 5 years[4–7]. Background and results from this study are presented in another paper[8] and only the mineralogical transformations over time are discussed here. In the second study, core samples of flue gas desulfurization CCB were recovered from disposal cells adjacent to a power plant. Core materials were originally disposed of in one cell starting in 1983 and in a second starting in 1986[9].

It has been found that over a period of years, contact of these landfilled cementitious CCBs with infiltrating surface or ground water, or merely extra moisture incorporated before closure of a landfill, can result in significant changes in crystalline and amorphous phase assemblages (typically referred to as 'mineral transformations'), accompanied by equally significant changes in physical properties. This process is analogous to natural diagenesis of sediments, in which originally deposited

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minerals are transformed at low temperatures and pressures into new minerals[6,10]. With access to sufficient moisture, chemical components are added and removed, crystallization continues, and first-formed crystalline phase assemblages are transformed into new assemblages. Diagenesis in natural materials is accompanied by changes in physical properties, such as the hardening of soft sediments into shale or the increase in porosity on conversion of limestone into dolomite (dolostone)[11]. The authors suggest that the term diagenesis be used to designate the combined physical, chemical and mineralogical changes that occur in a CCB after disposal.

EXPERIMENTAL

Five types of CCBs from four sites were studied:

1. Limestone injection multistage burner (LIMB). This CCB was a mixture of Class F fly ash produced in a low-NO_x burner, reacted sorbent (calcium sulfate) and unreacted sorbent (lime). Test cells were located near the power plant at Loraine, in northern Ohio. The climate here was moist throughout the test. Core samples were up to 5 years old. This material is referred to as OH LIMB.
2. Bubbling-bed atmospheric fluid bed combustion (AFBC). This CCB was a mixture of non-combustible coal components, reacted sorbent (calcium sulfate) and abundant unreacted sorbent (calcium oxide and hydroxide). Test cells were located at a mine site near Canton, in central Illinois. The climate here was moist throughout the test. Core samples up to 4 years old were collected, with a fifth year to be collected in 1996. This material is referred to as IL AFBC.
3. Blended fly ash–AFBC. This CCB was a blend of IL AFBC with an equal mass of a conventional Class F fly ash (FA), mixed with water at optimum field moisture (~30 wt% on a dry solids basis) and at 10% in excess of optimum field moisture. The test cells were also located at the site near Canton, Illinois, with a moist climate throughout the test. Core samples up to 2 years old were collected, with a third year to be collected in 1996. This material is referred to as IL AFBC + FA.
4. Circulating fluid bed combustion (CFBC). This CCB was a mixture of non-combustible coal components, reacted sorbent (calcium sulfate) and a small amount of unreacted sorbent (calcium oxide). Test cells were located in western Colorado in an arid climate. Core samples up to 5 years old were collected. This material is referred to as CO CFBC.
5. Dry-process FGD by-product from the second study. This CCB was a North Dakota lignite Class C fly ash mixed with reacted sorbent (calcium sulfite hemihydrate, calcium sulfate hemihydrate and dihydrate). Licensed disposal cells were located near the power plant at a strip mine site. The climate in this section of North Dakota is semi-arid, with most moisture coming from summer storms and spring snowmelt. Core samples were up to 11 years old. This material is referred to as ND FGD.

Chemical compositions of four of the five materials, expressed in oxide convention, are given in *Table 1*. Compositions are presented on a dry basis to permit more meaningful chemical comparisons. After conditioning, when the various CCBs were placed in the cells, the amount of H_2O [pore H_2O, crystalline H_2O and $(OH)^-$] ranged from ~20 to ~50 wt% on a dry solids basis. The composition of the Class F fly ash used for the composite material at the Illinois site is not available.

Crystalline phase assemblages in the core samples were determined using powder X-ray diffraction (XRD). The X-ray diffractograms shown here were obtained using Cu Kα radiation on instruments equipped with theta-compensating variable divergence slits. Detailed discussions of the mineralogy, hydration reactions and XRD characterization of CCBs have been presented previously[12–16]. *Table 2* lists the mineral names and nominal compositions of the crystalline phases discussed in this paper.

Microstructure characterization and elemental analysis by energy-dispersive spectroscopy were also performed on the core materials. Results for the materials from the Ohio and Illinois sites have been reported recently[17]. Results for the North Dakota site core materials will be submitted elsewhere.

RESULTS AND DISCUSSION

Chemical compositions

From the chemical compositions given in *Table 1*, it is seen that all four CCBs contain substantial calcium (CaO), aluminium (Al_2O_3) and sulfate (SO_3). The IL AFBC by-product is especially rich in calcium, speciated as $Ca(OH)_2$ and $CaSO_4$ (see below). Materials with compositions such as these are known to form ettringite (see *Table 2*) readily from the combination of high pH (~12.5) produced by the saturated $Ca(OH)_2$ solutions, soluble Al species dissolved from fly ash glass or

Table 1 Anhydrous oxide analyses (wt%) of by-products before placement in landfill cells[a]

By-product	OH LIMB	IL AFBC	CO CFBC	ND FGD
SiO_2	20.4	13.8	49.4	22.7–36.7
Al_2O_3	9.9	3.7	24.9	10.3–12.3
Fe_2O_3	11.4	4.4	3.4	5.1–5.3
CaO	35.9	54.2	12.5	20.0–25.6
MgO	0.8	1.0	0.7	5.8–6.6
K_2O	0.9	0.5	0.9	0.5–1.1
Na_2O	0.2	0.1	0.1	5.4–9.3
SO_3	15.3	18.9	5.8	10.4–15.8
CO_2	5.2	3.5	1.9	not available

[a] Analyses performed by C. M. Lillemoen and D. J. Hassett

Table 2 Selected mineral names and nominal compositions

Mineral name[a]	Nominal chemical composition
Anhydrite	$CaSO_4$
Bassanite	$CaSO_4 \cdot 1/2H_2O$
Calcite (Cc)	$CaCO_3$
Ettringite (Et)	$Ca_6Al_2(SO_4)_3(OH)_{12} \cdot 26H_2O$
Gypsum (Gp)	$CaSO_4 \cdot 2H_2O$
Hannebachite (Hb)	$CaSO_3 \cdot 1/2H_2O$
Lime	CaO
Nosean-hauyne	$(Na, Ca)_8Al_6Si_6O_{24}(SO_4)_{1-2}$
Portlandite (Pl)	$Ca(OH)_2$
Quartz (Qz)	SiO_2
Tobermorite (To)	$Ca_5Si_6O_{16}(OH)_2 \cdot 4H_2O$
Thaumasite (Tm)	$Ca_6Si_2(SO_4)_2(CO_3)_2(OH)_{12} \cdot 24H_2O$
Zeolite Na-Pl (Z)	$Na_6Al_6Si_{10}O_{32} \cdot 12H_2O$

[a] Codes in X-ray diffractograms are shown in parentheses

Table 3 Summary of results

Site and by-product	X-ray diffraction characterization	Comments
OH LIMB	By-products diagenesis by year 2. Portlandite and most gypsum gone. Ettringite retained. Abundant thaumasite formed. Steady-state phase assemblage retained for three additional years. Some regions with no thaumasite formation had higher strength.	Abundant moisture infiltration.
IL AFBC	By-products diagenesis begins by year 2. Ettringite retained. Thaumasite increases between year 2 and 3. Portlandite still abundant.	Abundant moisture infiltration.
IL AFBC + FA	No significant diagenesis 2 years after initial hydration phase assemblage formed. Ettringite retained. No thaumasite.	Moist climate, but little moisture infiltration.
CO CFBC	No significant diagenesis 5 years after initial hydration phase assemblage formed. Ettringite retained. No thaumasite.	Dry climate. Little moisture added while cell was open. No additional infiltration of moisture or contact with ground water.
ND FGD	Extensive diagenesis in these 9–12 year-old materials. Thaumasite formed and ettringite retained in some core samples. Other cores contain no ettringite/thaumasite, but have unique assemblage of Na-zeolite, tobermorite, nosean-hauyne and Na–Ca sulfate hydrate.	No general infiltration of moisture or contact with ground water. Moisture content from original conditioning and precipitation when cell open.

dehydrated FBC clay minerals, and sulfate[1–3]. Ettringite is the principal binder in these cementitious materials. Calcium silicate hydrate (C-S-H), the principal binder of ordinary Portland cement, also forms to varying extents. Although the composition of the Class F fly ash used in the composite material at the Illinois site is not available, a reasonable approximation, based on similar fly ashes in the North American Fly Ash Database[15], is 50–60 wt% SiO_2, 20–30 wt% Al_2O_3, 7–15 wt% Fe_2O_3 and <3 wt% CaO or SO_3. The purpose of mixing the high-SiO_2–Al_2O_3 fly ash with the high-CaO IL AFBC material was to provide more solubilizable Si and Al for pozzolanic reactions that would form more of the durable C-S-H binder phase, as well as more ettringite.

Mineralogy

Results from the first few years of monitoring and materials characterization are described in detail elsewhere[4–8,17]. The focus here is on the mineralogical transformations, as characterized by XRD, that constitute CCB diagenesis. *Table 3* summarizes the key observations from studies of the five materials from the four sites[4–8,17]. Discussion of these results by disposal site follows.

Ohio site. The X-ray diffractograms in *Figures 1A* and *1B* illustrate the diagenesis occurring in the OH LIMB CCB. Ettringite, gypsum and portlandite were the initial crystalline hydration products (*Figure 1A*). The broad increase in the baseline between 20 and 30° 2θ indicates a significant content of non-crystalline phase(s). After 2 years in the landfill cell, up to 80 wt% of the original material had converted to two crystalline hydrate phases (ettringite, $Ca_6Al_2(SO_4)_3(OH)_{12} \cdot 26H_2O$, and thaumasite, $Ca_6Si_2(SO_4)_2(CO_3)_2(OH)_{12} \cdot 24H_2O$), and this phase assemblage persisted in samples taken after 3 and 5 years (*Figure 1B*). This diagenesis was accompanied by significant losses in strength and increases in water permeability[4–8,17]. For example, core samples that exhibited compressive strengths of ~10 MPa after 3 months of burial had strengths of ~1 MPa after 5 years. The appearance of thaumasite and loss of gypsum accompanied the dramatic changes in physical properties. Finely divided calcite, often implicated[18] as the carbonate source for thaumasite formation, was present in all of the materials studied, including the OH LIMB material, having formed in the CCBs through the hydration and subsequent carbonation of the reactive, soft-burnt lime constituent of the by-products.

Interestingly, there were isolated zones of OH LIMB core in which thaumasite did not form and gypsum persisted (*Figure 1C*) even after 5 years[17]. There was a striking correlation between the amount of effort needed for core pulverization in XRD sample preparation and the thaumasite content. Thaumasite-rich samples were friable and could be crushed easily. Thaumasite-free samples were tough and had to be broken apart with a hammer. It is speculated that infiltrating moisture was channelled around these unaltered zones.

Illinois site. Two types of CCBs placed in separate test cells were studied. The IL AFBC core samples showed diagenetic behaviour similar to that observed at the Ohio site. Thaumasite formed, most of the gypsum was lost and ettringite persisted (*Figure 1D*).

The blends of IL AFBC by-products and fly ash, which were designed to have a higher proportion of durable, strength-producing calcium silicate hydrate (C-S-H), were studied three times over 2 years. With the exception of additional hydration of anhydrite to gypsum, the original phase assemblage underwent no significant diagenesis. To date, no thaumasite has formed. Correlation of mineralogy, physical properties and moisture availability is in progress. The absence of significant diagenesis may be due to the additional, less reactive, C-S-H in the cementitious matrix, or simply to insufficient moisture infiltration to continue hydration reactions and transport leached constituents within the materials. One additional year of core sampling is planned.

Colorado site. In the arid Colorado climate where the CFBC CCB test cell was located, by-product diagenesis was minimal, i.e. no significant change in crystalline phase assemblage was found in core samples collected at various times over 5 years[4–8].

North Dakota site. The core samples recovered from the North Dakota disposal cells showed remarkable and variable by-product diagenesis. Mineralogical characterization in this laboratory 10 years ago[19] on several samples of the by-product from the power plant gave the following results: (1) an assemblage of phases

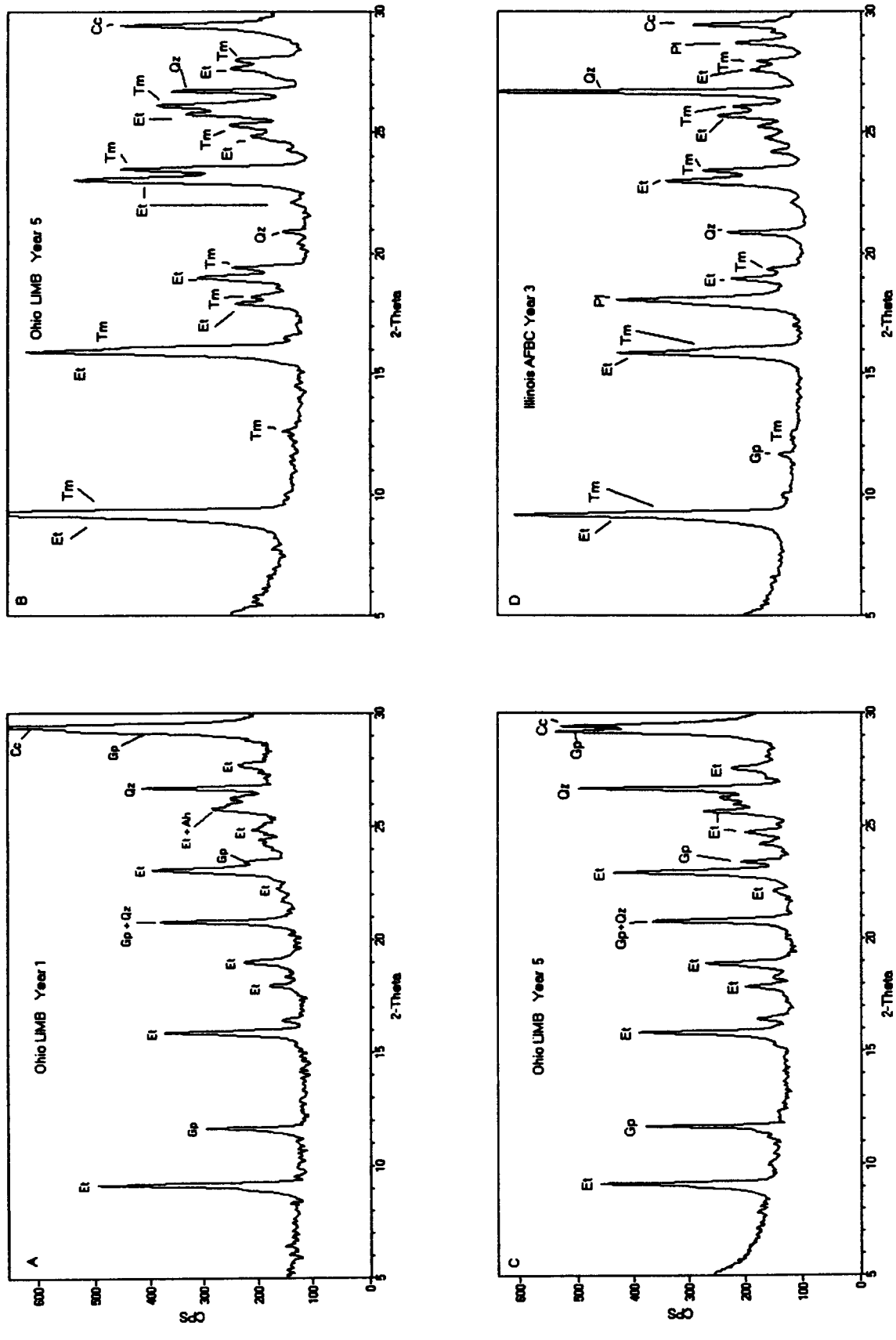

Figure 1 Portions of X-ray diffractograms of core samples from the Ohio and Illinois sites

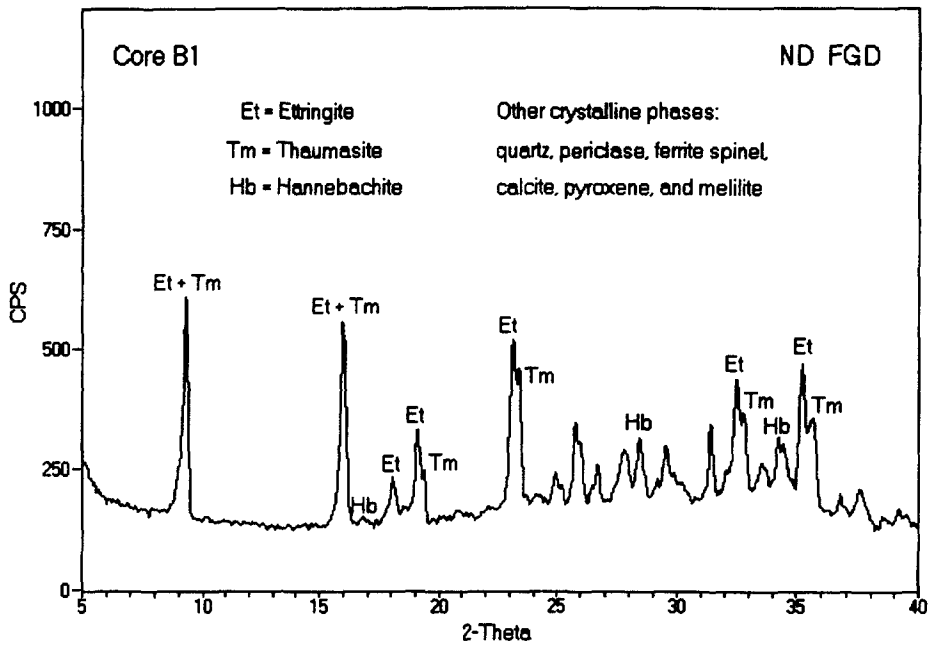

Figure 2 Portion of an X-ray diffractogram of one common ettringite + thaumasite phase assemblage in core samples from the

resulting from the dry scrubber process, calcium sulfite hemihydrate (hannebachite), calcium sulfate dihydrate (gypsum), and calcium sulfate hemihydrate (bassanite); (2) sodium sulfate (thenardite) and calcium sulfate (anhydrite); and (3) crystalline phases typical of high-sodium North Dakota lignite fly ash, including quartz, periclase, melilite, merwinite, tricalcium aluminate, ferrite spinel and haematite[10–14]. Except for tricalcium aluminate, this last group of phases is relatively inert during cementitious hydration reactions[1–3]. Bottom ash was also dumped in the cells. Bottom ash contains crystalline phases that are also largely unreactive during hydration reactions[19], plus glass that may participate in these reactions.

Figure 2 is representative of diffractograms from one type of diagenetic phase assemblage that occurred in about half of the core samples. The major crystalline phases were again ettringite and thaumasite. Some of the scrubber-phase hannebachite was still present, along with low-reactivity phases from the fly ash and bottom ash. In some of the oldest dumped material the proportion of thaumasite was greater than that shown in *Figure 2*.

Figure 3 is representative of diffractograms from the second type of diagenetic phase assemblage. The core sample contained no ettringite or thaumasite, but instead contained a crystalline calcium silicate hydrate phase known as tobermorite [$Ca_5Si_6O_{16}(OH)_2 \cdot 4H_2O$], Na-Pl zeolite ($Na_6Al_6Si_{10}O_{32} \cdot 2H_2O$), nosean-hauyne [$(Na, Ca)_8Al_6Si_6O_{24}(SO_4)_{1-2}$], and $Na_2Ca_5(SO)_4 \cdot 3H_2O$, in addition to residual hannebachite, fly ash and bottom ash crystalline phases. Although tobermorite is well

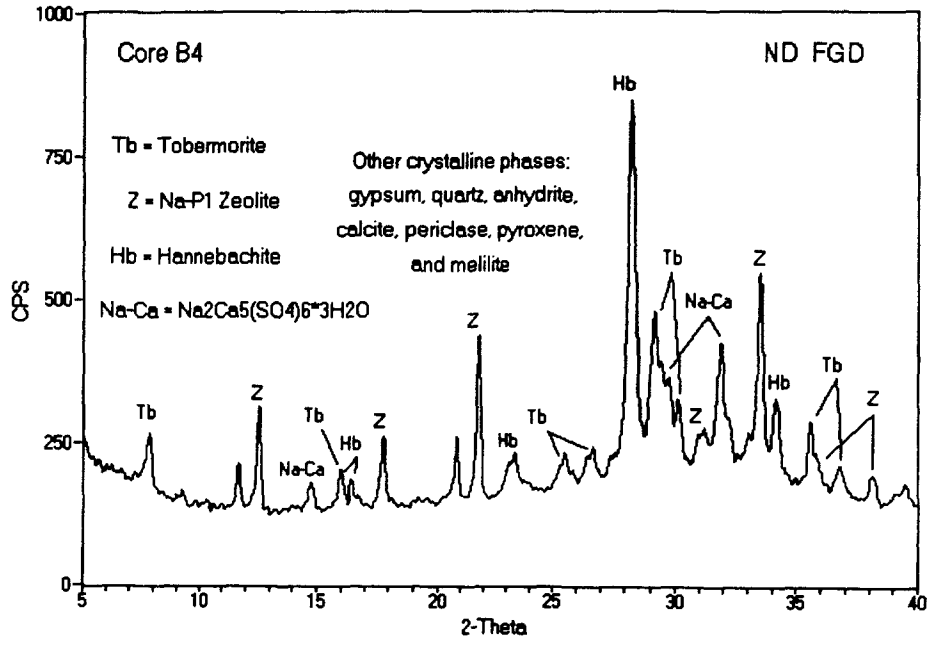

Figure 3 Portions of an X-ray diffractogram of a high-Na phase assemblage in core samples from the North Dakota site

known as a product of hydrothermal treatment of calcium silicates and concrete, this is the first observation of this phase forming in landfilled by-products under natural ambient conditions. The appearance of an Na-zeolite, the Na-rich nosean-hauyne solid solution phase and Na-Ca sulfate hydrate, and perhaps the tobermorite, may be a consequence of the high-Na, high-pH pore solution environment established by the high-sodium lignite CCB. Chemical analyses[9,19] of the original by-products gave Na_2O contents ranging from 5.4 to 9.3 wt%. Treatment of fly ash with warm NaOH solutions can produce the same Na-Pl zeolite observed in these disposed materials[20]. Tobermorite has recently been stated to form at temperatures as low as 90°C in the system Na_2O–CaO–Al_2O_3–SiO_2–H_2O (M. W. Grutzeck, personal communication). Except for a short period when hydration heat was at its maximum, this minimum temperature is well above the range expected in a dumped CCB.

Unlike those in the Ohio and Illinois sites, the materials in the North Dakota cells were generally protected from precipitation moisture by a soil cap. Apart from a high-moisture layer near the top of one cell, there appears to have been no general contact with ground or surface water[9]. The source of water necessary for diagenesis must reflect handling and disposal conditions, possibly including rainfall at the time of emplacement[9].

Thaumasite. The appearance of thaumasite in the OH LIMB and IL AFBC test cell core samples was accompanied by loss of much of the initial strength[4–8]. If thaumasite formation is not a major cause of strength loss, it is certainly associated with it. When this discovery was made in 1991 for the OH LIMB CCB[2–7], it was the first observation of thaumasite formation in advanced coal technology by-products exposed to environmental conditions. However, thaumasite formation is well known as a degradation mechanism in conventional Portland cement concrete, where the combination of cold wet conditions, sulfate-rich ground water and carbonation promotes attack of the C-S-H matrix and failure of the concrete. A recent report of thaumasite associated with failed concrete in the Canadian Arctic[18] gives an up-to-date summary of the literature on the association of thaumasite with degradation of conventional concrete.

Implications for coal combustion by-products utilization

The initial behaviour observed on hydration of the cementitious CCB materials discussed here is similar to that of a low-strength concrete. However, diagenesis associated with many of these CCBs reduced the strength by up to 90% and increased the permeability by two orders of magnitude after only a few years in the natural environment. The characteristics of the altered by-products resemble those of soils more than concrete. The results of this study should be noted by those working on utilization of this class of by-products for civil engineering and construction applications, manufacture of aggregates, etc. Initially promising 7 or 28 day laboratory tests on strength and permeability may not be characteristic of these materials on exposure to the environment. Blending of CCBs with fly ash to increase the proportion of cementitious C-S-H, and controlling subsequent moisture additions, could minimize deleterious by-product diagenesis. Alternatively, for some applications, it might be desirable to design a system where by-product diagenesis is allowed to develop naturally[8].

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REFERENCES

1 Solem, J. K. and McCarthy, G. J., in *Advanced Cementitious Systems*. Materials Research Society Symposium Proceedings, Vol. 245. Pittsburgh, 1992, p. 71.
2 McCarthy, G. J., Bender, J. A., Solem, J. K. and Eylands, K. E., in *Proceedings of the Tenth International Ash Use Symposium*. EPRI TR-101774s. Electric Power Research Institute, Palo Alto, CA, 1993, p. 58/1.
3 McCarthy, G. J. and Solem-Tishmack, J. K., in *Advances in Cement and Concrete*, (ed. M. W. Grutzeck and S. L. Sarkar). American Society of Civil Engineers, New York, 1994, p. 103.
4 Weinberg, A., Petrini, R. H. and Butler, R. D., Advanced coal technology waste disposal. Draft final report prepared for US Department of Energy, Morgantown Energy Technology Center, 1993.
5 Weinberg, A., Coel, B. J. and Butler, R. D., Field study for disposal of solid wastes from advanced coal processes: Ohio LIMB site assessment. Final Report No. DOE/MC/22118-3969 (DE950000053), Radian Corporation, Austin, TX, 1994.
6 Butler, R. D., Brekke, D. W., Foster, H. J., Solc, J. and McCarthy, G. J., in *Proceedings of the Seventeenth Biennial Low-rank Fuels Symposium*. UND Energy and Environmental Research Center, Grand Forks, ND, 1993, p. 515.
7 Butler, R. D., in *Proceedings of the 10th Annual International Pittsburgh Coal Conferences*. Pittsburgh, 1993.
8 Weinberg, A. and Hemmings, R. T., *Fuel*, 1997, **76**, 705.
9 Butler, R. D. and Pflughoeft-Hassett, D. F., Diagenesis and leaching characteristics of aged coal conversion solid residues from mine disposal environments. Report ND08, UND Energy and Environmental Research Center, Grand Forks, ND, 1995.
10 Faure, G., *Principles and Applications of Inorganic Geochemistry*. Macmillan, New York, 1991.
11 Krauskopf, K. B., *Introduction to Geochemistry*, 2nd edn. McGraw-Hill, New York, 1979.
12 McCarthy, G. J., Swanson, K. D., Keller, L. P. and Blatter, W. C., *Cement and Concrete Research*, 1984, **14**, 471.

13 McCarthy, G. J., in *Fly Ash and Coal Conversion By-Products: Characterization, Utilization and Disposal IV*. Materials Research Society Symposium Proceedings, Vol. 113. Pittsburgh, 1988, p. 75.
14 McCarthy, G. J., Johansen, D. M., Thedchanamoorthy, A., Steinwand, S. J. and Swanson, K. D., in *Fly Ash and Coal Conversion By-Products: Characterization, Utilization and Disposal IV*. Materials Research Society Symposium Proceedings, Vol. 113. Pitsburgh, 1988, p. 99.
15 McCarthy, G. J., Solem, J. K., Manz, O. E. and Hassett, D. J., in *Fly Ash and Coal Conversion By-Products: Characterization, Utilization and Disposal VI*. Materials Research Society Symposium Proceedings, Vol. 178. Pittsburgh, 1990, p. 3.
16 McCarthy, G. J. and Solem, J. K., in *Advances in X-Ray Analysis*, 1991, **34**, 387.
17 McCarthy, G. J., Adamek, S. D., Butler, R. D., Parks, J. A., Brekke, D. W., Foster, H. J. and Solc, J., in *Microstructure of Cement-Based Systems*. Materials Research Society Symposium Proceedings, Vol. 370. Pittsburgh, 1995, p. 179.
18 Bickley, J. A., Hemmings, R. T., Hooton, R. D. and Balinski, J., in *V. Mohan Malhotra Symposium: Concrete Technology Past, Present, and Future*, ed. P. K. Mehta. ACI SP-144, American Concrete Institute, Detroit, 1994, p. 159.
19 Stevenson, R. J., Hassett, D. J., McCarthy, G. J., Manz, O. E. and Groenewold, G. H., Solid waste codisposal study. Final Report to the Gas Research Institute, ND Mining and Minerals Research Institute, UND-EERC, 1989.
20 Querol, X., Plana, F., Alastuey, A. and López Soler, A., *Fuel* (this issue).