

**CHEMICALLY BONDED PHOSPHATE CERAMICS:  
CEMENTING THE GAP BETWEEN CERAMICS AND CEMENTS\***

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**Chemically Bonded Phosphate Ceramics:  
Cementing the Gap between Ceramics, Cements, and Polymers**

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An overview of chemically bonded phosphate ceramics (CBPCs), that fill the gap between cements and conventional ceramics, is provided. CBPCs are synthesized by chemical reactions, most of them at ambient conditions, and hence are most useful in high volume applications. These applications include stabilization of hazardous and radioactive wastes, various structural materials applications, including road repair, oil well cements, and architectural products. The products are mainly magnesium and iron-phosphate ceramics. Specialty formulations have also been developed for biomaterials applications using calcium-phosphate-based ceramics. This article reviews the chemistry of syntheses of these materials, using magnesium iron and aluminum phosphate ceramics as representative examples, provides a summary of their properties and an overview of their niche applications.

**Introduction**

Sintered ceramics have served a critical need since the beginning of human culture. They have been used in pottery and rudimentary tools over thousands of years, and their analysis in archaeological studies has told us much about human culture in distant times. Ceramics are also modern technological materials, especially in high temperature applications, and constitute an intense field of research even today.

Sintering, however, is energy intensive and expensive when implemented on a large scale. The alternative is chemical bonding. Portland cement is a good example of this alternative. Formed by chemical reactions, it is an inexpensive product and, hence, can be used in high volumes. There is a wide gap between the attributes of sintered ceramics and Portland cement. While expensive compared with cement, ceramics have superior mechanical properties and ceramics are far more stable in acidic and high temperature environments. Modern technological needs are not fulfilled entirely by these two types of materials. Often there is a need for materials with properties in between. Chemically bonded ceramics can fulfill this need. In particular, chemically bonded phosphate ceramics (CBPCs) have been developed sufficiently during the last decade that they are poised to fill this gap between cements and ceramics.

CBPCs are formed by acid-base reactions between an acid phosphate (such as that of potassium, ammonium, or aluminum) and a metal oxide (such as that of magnesium, calcium, or zinc). Zinc phosphates were developed as dental cements and were in use during the first half of the twentieth century [1]. Subsequently, Brookhaven National Laboratory developed magnesium ammonium phosphate cements [2] and calcium-aluminate-based CBPCs [3] as rapid-setting cements. Recently, Argonne National Laboratory developed a magnesium potassium phosphates (called Ceramicrete) [4], to fulfill the need for materials to stabilize and encapsulate radioactive and hazardous waste streams stored within the U.S. Department of Energy's complex.

CBPCs are now finding their use in several fields. In addition to waste management applications, they are being considered for simple road repair during winter, development of novel architectural products, improved oil-field cements, even advanced bone and dental cements, all based on superior properties of CBPCs and their formation at ambient temperature. This paper provides an overview of these materials and their wide range of applications.

## **Solution Chemistry as Key to Forming CBPCs**

When a metal oxide is stirred in an acid-phosphate solution, it dissolves and forms cations that react with the phosphate anions to form a phosphate gel. This gel subsequently crystallizes and consolidates into a ceramic. Dissolution of the oxide also raises the pH of the solution, with the ceramic being formed at a near-neutral pH. The CBPC is produced by controlling the solubility of the oxide in the acid-phosphate solution. Oxides or oxide minerals of low solubility are the best candidates to form CBPCs because their solubility can be controlled easily. Such oxides are categorized as “sparsely soluble solids.”

Most of the oxides of divalent and trivalent metals are sparsely soluble. Even among these, however, the solubility covers a very wide range. Generally, divalent metal oxides have a higher solubility than trivalent metal oxides. For example, the solubility product constant,  $pK_{sp}$ , of divalent magnesium oxide (MgO) is equal to 11.25, while the constants for trivalent metal oxides such as alumina ( $Al_2O_3$ ) and iron oxide ( $Fe_2O_3$ ) are 24.05 and 44.06 [5]. An increase of  $pK_{sp}$  by one number implies that the solubility is lower by an order of magnitude; thus, the solubilities of alumina and iron oxide are 13 and 23 orders lower than that of magnesium oxide. Iron oxide also exists in a divalent oxide state, FeO, and has a  $pK_{sp}$  of 16.3. Thus, this oxide is much more soluble than its trivalent counterpart.

To form CBPC, the solubility of divalent metal oxides is adequate or slightly higher than needed, while the solubility of trivalent metal oxides is too low. As shown in Figure 1, the solubility, represented as the concentration for the corresponding metal ion, initially decreases as the pH increases during the acid-base reaction. For magnesium oxide, it steadily decreases, while for iron oxides and alumina, it reaches a minimum and then increases, exhibiting amphoteric behavior. Also notice that the solubility of divalent metal oxides is much higher than that of trivalent metal oxides in acidic and neutral regions. The solubility needed to form ceramics is somewhere in between these two metal oxides. Therefore, to form a ceramic, one must lower the solubility of magnesium oxide and increase the solubility of alumina and

trivalent iron oxide. In the following discussion, we illustrate how the solubility can be adjusted to form ceramics from these three oxides.

#### Magnesium Phosphate Ceramics:

To reduce its solubility, magnesium oxide is calcined at 1300 °C so that its grains are well crystallized, and micropores from the grains are removed. Such “dead burnt” magnesium oxide can then be reacted at room temperature with any acid-phosphate solution, such as ammonium or potassium dihydrogen phosphate, to form a ceramic of either magnesium ammonium or magnesium potassium phosphate [2, 6]. When the powder is stirred in the solution, it forms a paste that sets within an hour. This method is well suited for making ceramics of small size, i.e., for filling a pothole with a gallon volume of paste.

While making large samples, like in a drum to stabilize large volume waste streams, the reduced solubility of the calcined magnesium oxide is still too high, and the acid-base reaction is too rapid because the large amount of exothermic heat generated raises the temperature and accelerates the reaction. In such cases, a very small amount (<1% of the total powder) of boric acid is used as a retardant. This boric acid reacts with the acid-phosphate and forms a temporary coating of lunebergite [7], a magnesium boron phosphate on the surface of oxide particles which prevents the dissolution of magnesium oxide into the solution. As the oxide powder is mixed in the acid solution, however, the coating itself dissolves and exposes the oxide particle surface to the acid solution, and magnesium oxide then starts dissolving into the solution. This boric acid addition reduces the rate of reaction and provides sufficient time for the acid-base mixing to yield practical ceramics.

### Aluminum Phosphate Ceramics

The solubility of alumina can be enhanced by simply raising the temperature of the acid-base solution to 150 °C. On the basis of the thermodynamics of oxide dissolution, the solubility product constant for alumina reaches a maximum at 118°C [8]. At this temperature, the solubility is sufficiently increased that the alumina particles can be partially dissolved in phosphoric acid solution to form a gel containing  $\text{AlH}_3(\text{PO}_4)_2 \cdot \text{H}_2\text{O}$ . This gel reacts with alumina at 150 °C to form a ceramic of berlinite ( $\text{AlPO}_4$ ). The end product is a hard ceramic of berlinite.

### Iron Phosphate Ceramics

In the case of iron oxide, the solubility can be enhanced by the simple reduction of trivalent to divalent iron by using a small amount of elemental iron [9]:



As shown in Figure 1, FeO has a much higher solubility than  $\text{Fe}_2\text{O}_3$ . Thus, the reduction represented by Equation (1) enhances the solubility of individual  $\text{Fe}_2\text{O}_3$  surface, which will then react with the acid solution to form hydrophosphates of iron. The reaction products bind the particles, and a ceramic is formed.

The three examples given above demonstrate how the solution chemistry plays a key role in forming CBPCs. The methods can be applied to other divalent and trivalent metal oxides and even to quadrivalent metal oxides, such as zirconium oxide, which is nearly sparsely soluble.

## **Versatile Ceramics from Cement-Like Fabrication Process**

CBPCs are formed by stirring a powder mixture of oxides and additives such as retardants and fillers into a phosphate solution. In the case of magnesium potassium phosphate, a mixture of MgO and  $\text{KH}_2\text{PO}_4$  can simply be added to water and mixed from 5 min to 25 min, depending on the batch size.  $\text{KH}_2\text{PO}_4$  dissolves in the water first and forms the acid-phosphate solution in which MgO dissolves and

reacts with the phosphate and sets into a ceramic. This process mimics that of conventional cement, and hence, this product is named “Ceramicrete” (a ceramic with a fabrication process similar to concrete). In the case of iron phosphate, the process is similar except that a mixture of  $\text{Fe}_2\text{O}_3$  and a very small amount of Fe (<1 wt.%) are mixed with a dilute solution of  $\text{H}_3\text{PO}_4$  to form a ceramic. In the case of aluminum phosphate ceramic, the mixing procedure is again similar, but the mixture needs to be heated to  $150^\circ\text{C}$ .

A considerable amount of mineral and other industrial waste can be added to these ceramics, thereby reducing their cost. A good example is Ceramicrete, one of the most versatile CBPCs, in which various industrial byproduct waste streams have been added to recycle benign wastes and produce value-added products. Table 1 lists some of these waste streams and potential products or applications.

In general, any inorganic waste stream can be added to CBPCs, as long as their loss on ignition (LOI) values are sufficiently low. If LOI is high (typically >8 wt.%), evolution of gases (such as  $\text{CO}_2$ ) during the acid-base reaction makes the products porous, and this increased porosity reduces the strength and integrity of the products. In practice, such waste streams can be pretreated with a dilute phosphoric acid solution to eliminate these gases and they can then be used in formation of the ceramic. Thus, virtually any inorganic waste streams, in particular mineral waste streams, can be used to develop structural products.

One of the major advantages of the versatility of CBPCs is that materials with a desired property can be produced by adding suitable minerals. The binders by themselves exhibit physical properties similar to conventional cement. For example, the compressive strength of magnesium phosphate-based CBPCs is between 21 and 28 MPa (3000 and 4000 psi), comparable to that of portland cement. Moreover, when Class F and Class C fly ash is added at 60 wt.% loading, the compressive strength increases to 55 and 83 MPa (8000 and 12,000 psi) [10], respectively. This property makes the CBPC

processes well suited for high-volume waste products. In these processes, waste recycling is not only an advantage, it is a necessity.

Table 2 lists the properties of CBPCs with various additives, including the particular application for which the product is intended. For the sake of comparison, it also gives corresponding typical properties in conventional cements. The data in Table 2 show that, overall, the properties of CBPCs are superior to those of conventional cement. The cost, however, is higher than that of cement. Among the three candidate formulations described earlier, the one containing Mg phosphate (such as Ceramicrete), ash, and aggregates is still at least two times more expensive than conventional cement. Typically, the retail price is  $\phi$ 3-4/lb ( $\phi$ 6.6-8.8/kg) for cement and  $\phi$ 10-12/lb ( $\phi$ 22-26/kg) for Mg-based CBPC. Because of this discrepancy, Mg-based CBPCs are being considered for niche markets, where conventional cement formulations are not suitable. Aluminum-phosphate ceramics are even more expensive because some heat treatment is needed to form them. Thus, Al-based ceramics have more limited use; one possibility is in casting refractories in proper shapes prior to firing.

Phosphate ceramic formed by iron-oxide, called Ferroceramicrete, is comparatively cheap, costing the same as cement. It also has nearly the same strength characteristics as cement but has advantages of rapid setting, better stability over a range of pH, and other attractive properties such as bonding to itself.

Figure 2 shows scanning electron photomicrographs of the three CBPCs discussed above. Ceramicrete has a highly crystalline structure; Al phosphate, a granular structure; and Ferroceramicrete, an amorphous or glassy structure. In the case of Ceramicrete, most of the matrix is  $\text{MgKPO}_4 \cdot 6\text{H}_2\text{O}$  crystals. With the Al phosphate, berlinite forms only on the surface of individual alumina particles and binds these particles, and hence, is this CBPC granular. Ferroceramicrete is formed by rapid setting of the gel and, hence, is amorphous.

### **Niche Applications**

Potential applications of CBPCs fall into the following three categories:

- Stabilization of radioactive and hazardous waste,
- Architectural and construction products formed by recycling benign wastes and oil-field cements, and
- Bone and dental cements.

These different applications are possible because CBPCs can be made with very high loading of either waste materials or aggregates. They also can incorporate waste materials over a wide pH range. In addition, like cement, most CBPCs except aluminum phosphate, are formed at ambient temperature. Figure 3 illustrates these attributes of CBPCs in comparison with conventional cements.

Because of the high loading of aggregates possible, the properties of a CBPC as listed in Table 2 can be modified easily. For example, a heavy Ceramicrete of density  $>3 \text{ g/cm}^3$  may be produced by adding iron oxide at a loading of  $>60 \text{ wt.}\%$ , while a light-weight Ceramicrete of density  $< 1 \text{ g/cm}^3$  may be produced by adding hollow silica spheres (Cenospheres) at a loading of  $50 \text{ wt.}\%$ . In addition, the high loading allows stabilizing hazardous and radioactive wastes in smaller volumes of waste forms and recycling larger volumes of benign wastes into useful products. Details of the above applications that make use of these attributes are given below.

#### Stabilization of Radioactive and Hazardous Waste

Stabilization technologies that have been considered during the second half of the last century are glass for high-level nuclear waste and cement for high-volume and low-level waste. Both have not been entirely satisfactory in performance. Vitrification of high-level waste requires intense heat treatment and has a potential to generate hazardous and radioactive volatiles that need to be captured and stabilized. The process also contaminates furnaces and other equipment that would need proper disposal.

Cements, being inherently porous, do not produce sufficiently nonleachable stabilized forms for several waste streams, and their cement chemistry is not compatible with certain chemical wastes such as acids.

During formation of CBPCs, if an inorganic waste is incorporated, the contaminants will also be converted into phosphates. Phosphates of these hazardous contaminants have a much lower solubility than their oxides or other salts. Thus, during formation of a stabilized product, the contaminants are converted into nonleachable phosphate products. At the same time, they are physically encapsulated in a dense phosphate matrix. This dual mechanism of chemical immobilization and physical encapsulation is very effective [4].

The ability of a material to immobilize hazardous contaminants is measured by the U.S. Environmental Protection Agency's (EPA's) Toxicity Characteristic Leaching Procedure (TCLP) [14]. The stabilized waste matrix is crushed to a particle size of 9.5 mm, and then leaching is conducted with an aqueous solution at a pH that simulates acid-rain conditions. The level of contaminants is measured in the leachate and is compared with the minimum prescribed by EPA's Universal Treatment Standards (UTS). Table 3 summarizes the leaching data on some of the tests using Ceramicrete. This table shows that the contaminant leaching are typically about one order of magnitude smaller than the UTS limits. These data illustrate the effectiveness of the chemical immobilization and physical encapsulation rendered by the phosphate matrix. These results are particularly important in the case of Hg, because the UTS limit is very low and difficult to attain with other technologies. Meeting this limit has been demonstrated by encapsulation of several waste streams in the CBPC matrix [15]. Introducing a small amount of sodium or potassium sulfide converts the mercury to its most insoluble form, mercury sulfide, which is then encapsulated in the CBPC matrix.

In the case of radioactive contaminants, the solubility issue is twofold. The first issue involves the oxides of transuranics, such as  $\text{UO}_2$  and  $\text{PuO}_2$ , which are insoluble in water. They are also the most stable compounds in most waste streams but are dispersible if the waste streams are powders or sludge. For this reason, these waste streams should be solidified in a dense and hard matrix prior to their

storage in repositories. Leaching of the radioactive species from the waste form can occur by diffusion. Therefore, it is necessary to measure the diffusion constant of these radioactive contaminants when such a stabilized waste form is immersed in water. In the 90-day immersion test of the American Nuclear Society (ANS 16.1) [16], this diffusion constant is measured and expressed as a leaching index that is negative log of the diffusion constant.

The second issue involves the fission products. Radioactive isotopes of Cs, Sr, Ba, and Tc are more soluble than transuranics and can leach out in a manner similar to hazardous metals. In particular, Tc in a valence state of +5 has a tendency to convert into +7 (in a chemical form called pertechnetate), which is more soluble and can leach from the waste form into groundwater easily. Addition of a very small amount of tin chloride to the Ceramicrete matrix during stabilization retains Tc in the lower oxidation state and immobilizes it.

The effectiveness of the phosphate matrix in immobilizing radioactive contaminants may be seen in the leaching indices presented in Table 4. For comparison, the leaching index for Tc in cement is 6 [20]. These results demonstrate the effectiveness of phosphate materials containing radioactive contaminants: the CBPC matrix is as effective as vitrified glass but does not have the drawbacks of vitrification.

In addition to stabilizing contaminated waste streams, CBPC can also be used in macroencapsulating large equipment and components. For example, we have encapsulated a radioactively contaminated spool of a wire to reduce the radiation level from 700 disintegrations per minute (dpm) to an acceptable level of 150 dpm for transportation and disposal. In a collaborative study involving the Russian Federation Research Center at Arzamas – 16, ANL, and Eagle Picher Industries, the CBPC matrix was evaluated for its ability to encapsulate large-scale nuclear materials for transportation and storage. The effect of freeze-thaw and fire resulting from an accident was evaluated. Model calculations showed that these materials would pass these tests. The details will be published elsewhere.

In summary, the CBPC matrix can chemically stabilize hazardous contaminants and fission products, and it can encapsulate radioactive elements and large-scale contaminated equipment. Such versatility is not found in any other material.

#### Recycling of Benign Wastes in Value-Added Products

CBPC processes are ideal for recycling high-volume waste streams and converting them into value-added products because a very high waste loading (in the range of 60 – 80 wt.%) is possible in these materials. Examples of these waste streams include industrial combustion residues such as fly ash from utility plants, mineral wastes such as red mud from alumina plants, machining wastes (swarfs) from iron and steel industries, and natural wood fibers. Some of these waste streams, in fact, improve the performance of the CBPC products and, hence, are considered part of the formulation. For example, Class F and Class C fly ash increases the compressive strength of the CBPC matrix from ~28 MPa ( $\approx$ 4000 psi) to 56 and 83 MPa (8000 and 12000 psi), respectively [10]. The resulting products are dense and pore free. Because of these superior properties, ash is an integral component in several CBPC products used or proposed for use for road repair during winter seasons, oil well cements, and novel architectural products.

Adding fibers result in a similar improvement in the strength of the products. In general, these fibers improve the flexural strength of the products significantly. For example, adding 3 wt.% glass fibers of 13-inch length enhances the flexural strength of Ceramicrete products from 6 MPa (900 psi) to as much as 11 MPa (1600 psi). Also, CBPC can bind natural fibers such as corn stalk, wood chips, or saw dust to generate value-added products for construction materials [12]. The main advantage here is that the products are fire resistant, and unlike polymer binders such as urea formaldehyde, do not produce harmful gases in the presence of fire. CBPC products are safe for the workers that produce them and for the users.

Red mud, a highly alkaline residue from the Bayer process extraction of alumina from bauxite, may be used for development of similar products. Because red mud contains very high concentrations

of hematite ( $\text{Fe}_2\text{O}_3$ ), structural materials can be prepared by the reduction described earlier (Equation 1). The advantage in this case is very high loading, ranging from 80 to 85 wt.% [21].

The performance of CBPC value-added products is key to their commercial success. CBPC products, when used with high volumes of benign waste streams, are still two to three times more expensive than conventional cement products. However, they also exhibit superior properties and are, therefore, seen to have niche applications where conventional cement products fail. For example, one key application of CBPCs that may not depend on cost is use as an oil-field cement. Brookhaven National Laboratory [3] and Halliburton Energy Services [22] have developed calcium-aluminate-based phosphate cements for oil-field applications. These cements are made from reaction of calcium aluminate with a phosphate source that forms a slurry, which sets in geothermal wells at 400 °C. These cements do not deteriorate in the presence of carbon dioxide in geothermal wells.

The major parameters that affect setting of CBPCs in downhole environments are temperature and pressure. The temperature ranges from 27°C for a shallow well to ~150°C for a deep well of 6096 m (20,000 ft). Correspondingly, the pressure ranges from 5 MPa (700 psi) to 117 MPa (17,000 psi). Under normal conditions, CBPCs are fast-setting cements, and the setting is accelerated by elevated temperatures and pressures. Even conventional cements flash-set in such environments. In an ongoing project, we have developed CBPC sealants that provide a pumping time of 3-5 h for shallow to deep wells. These sealants are still under development, but if successful, CBPCs will have a market for large-scale use in oil fields.

### Bone and Dental Cements

As mentioned earlier, the first CBPCs were zinc-phosphate-based dental cements. A recent thrust has been in developing CBPCs that are more biocompatible. Biological systems form bone and dentine at room temperature. Therefore, it is natural to expect that biocompatible ceramics should also be formed at ambient temperature, preferably in a biological environment, when placed in a body as a

paste. CBPCs hold good promise toward producing materials similar in composition, if not in exact structure, to bone.

A typical bone consists of a ceramic that is a combination of minerals, 69 wt.% of which is hydroxyapatite ( $\text{Ca}_5(\text{HPO}_4)_3(\text{OH})$ ), with the rest being other calcium phosphate compounds [23]. Substitutions for Ca include K, Mg, and Sr, while OH substitutions include Na and F. These substitutions play significant roles in the structure and mechanical properties of bones.

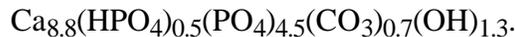
Bone is a light-weight material. Most of the orthopedic replacements currently used, such as steel, titanium, and alumina, are much denser than bone. Comparatively, CBPC materials are fairly close to the density of compact bone. Moreover, calcium-based CBPCs are biocompatible with bone and dentine. They can be formed at room temperature as a paste and placed in the body, where they harden and form a suitable microstructure, simulating biological materials. Mainly for the reason of biocompatibility, recent development in bone and dental cements has concentrated on calcium-based CBPCs. In particular, formulations that produce hydroxyapatite have been major candidates as CBPC bioceramics.

Hydroxyapatite can be formed by the reaction of either anhydrous dicalcium phosphate ( $\text{CaHPO}_4$ ) or dicalcium hydrophosphate dihydrate ( $\text{CaHPO}_4 \cdot 2\text{H}_2\text{O}$ ) and tetracalcium phosphate ( $\text{Ca}_4(\text{PO}_4)_2\text{O}$ ), given by the following reaction [24,25],



Adding phosphoric acid to the solution expedites the reaction. The compressive strength of these ceramics is 34 MPa ( $\approx 5,000$  psi), more than that of portland cement. Most of this strength is gained within a day [26].

Even hydroxyapatite does not produce a composition exactly the same as the mineral in bone. Bone contains carbonated and fluorinated hydroxyapatite. Constanz et al. [27] synthesized a carbonated apatite called dahllite, which is given by the stoichiometric formula



They produced dahllite by reacting a mixture of monocalcium phosphate monohydrate ( $\text{Ca}(\text{H}_2\text{PO}_4)_2 \cdot \text{H}_2\text{O}$ ),  $\alpha$ -tricalcium phosphate ( $\text{Ca}_3(\text{PO}_4)_2$ ), and calcium carbonate ( $\text{CaCO}_3$ ) with a solution of trisodium phosphate ( $\text{Na}_3\text{PO}_4$ ). The mixture formed from the ingredients was applied as a paste that set within minutes under simulated physiological conditions. The mixing time was  $\approx 5$  minutes, and the paste set by crystallizing into dahllite in another 10 minutes. The initial compressive strength was  $\approx 10$  MPa and increased to  $\approx 55$  MPa within 24 h. When completely set, its tensile strength was  $\approx 2.1$  MPa. The compressive strength is approximately the same as that of cancellous bone, while the tensile strength appears to be lower than that of a bone. The crystallite sizes of bone and this biomaterial were very similar equal to an average size of 5 nm. The density of the new biomaterial is  $1.3 \text{ g/cm}^3$ , and the average pore diameter was 30 nm.

The dahllite was clinically tested [26] as an implant for internal stabilization of a wrist fracture by injection. The material was allowed to harden in situ before castings of the wrist. The healing process was faster than with conventional techniques. The six-month grip strength surpassed that of two-year average value determined from the historical controls.

## **Conclusion**

Research on CBPC materials during the last decade has made significant advances. On the basis of solution chemistry principles, a range of CBPCs can be now produced. Tailored CBPCs are possible partially by selecting appropriate oxides or minerals and phosphate solutions. High-volume benign wastes and aggregates may be added to manipulate the CBPC properties. Production of versatile CBPCs has opened up wide-ranging applications for these materials that neither cement nor ceramics can match. Thus, these materials have the potential to close the commercial gap between ceramics and cements.

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Table 1. Industrial waste streams as additives in Ceramicrete and potential applications

Waste stream	Waste loading (wt.%)	Potential applications
Class C and F fly ash from power plants, steel slag, other combustion products [10]	40-80	Structural ceramics, superior cements, waste management
Red mud, an alkaline mineral waste from Bayer process extraction of alumina [9]	50-60	Structural products
Swarfs, a machining waste from steel and automobile industry [9]	50	Metal recycling
Contaminated soil [11]	50	Stabilization and safe disposal
Shredded styrofoam [12]	80	Insulation panels

Table 2. Typical properties of CBPC products and cement

CBPC Composition	Property	Property in CBPC	Application	Property in Cement
Ceramicrete and ash	Setting time	1–7 h	Structural ceramics, oil well cements, waste encapsulation	First setting at 6 h
All types	Setting pH	7-8	All	≈ 11
Ceramicrete and ash	Density	1.7–2.0 g/cm <sup>3</sup>	Any, Density can be varied by adding aggregates	2.4 g/cm <sup>3</sup>
All types	Volume change during setting	Slight expansion	Architectural moldings, oil well cements	Slight contraction
Ceramicrete and ash	Compressive strength	55-83 MPa (8,000–12,000 psi)	Structural ceramic, waste management	28 MPa (4,000 psi)
Ceramicrete, ash, and 1–3% glass fiber	Flex. strength	90-119 MPa (1300 – 1700 psi)	Macroencapsulation of rad. wastes, structural ceramics	5 MPa (~700 psi)
Ceramicrete with ash and sand	Fracture toughness	0.6 – 0.7 MPa√m	Structural ceramic	≈ 0.3 MPa√m
Borated Ceramicrete	Heat conductivity	≈ 0.53 W/mrk	Radioactive waste encapsulation	1.28 W/mrk
Borated Ceramicrete	Linear expansion coeff.	≈ 1.7 x 10 <sup>-7</sup> /°C	Macroencapsulation of contaminated equipment	1.2 x 10 <sup>-5</sup> /°C
Borated Ceramicrete [13]	Neutron abs. Coeff.	3.08 cm <sup>-1</sup>	Encapsulation of nuclear materials	0.06 cm <sup>-1</sup>
Ceramicrete, ash, aggregates [10]	Water absorption	<1 wt.%	All	5-15 wt.%
All types	Durability in water at given pH	3 -11	Stabilization of acids and alkalis, resistance to acid rain	7 and above

Table 3. Major results of TCLP tests conducted on Ceramicrete-stabilized hazardous wastes

Waste stream	Contaminant Concentration in waste	Loading (wt.%)	Leaching level (mg/L)	UTS limit (mg/L)
	Pb, 11.3 wt.%	35	<0.1	0.37
Ash [4]	CdO, 0.5 wt.% Cr <sub>2</sub> O <sub>3</sub> , 0.5 wt.% NiO, 0.5 wt.%	50 50 50	0.09 <0.05 0.21	0.19 0.86 5.00
Simulated DOE ash waste [15]	HgCl <sub>2</sub> , 0.5 wt.%	50	0.00085	0.025

Table 4. Leaching indices (L.I.) for various radioactive contaminants in the Ceramicrete matrix

Contaminant	Waste stream	Level in waste	Loading	L.I.
<sup>238</sup> U	Waste water	32 pCi/mL	57%	14.52 [11]
Pu (Ce as surrogate)	TRU in ash from Rocky Flats, a DOE site	31.8% as PuO <sub>2</sub>	24.75%	19.7 [17]
Cs	Waste water	8.3 pCi/mL	57%	>14.85 [18]
Tc	Partitioned from simulated Hanford high-level tank waste	Precipitated Tc ≈100 wt.%	903 ppm	14.6 [19]

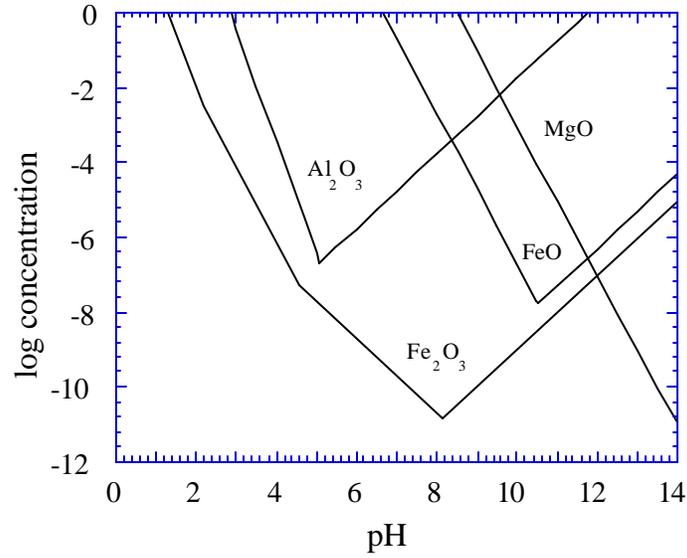
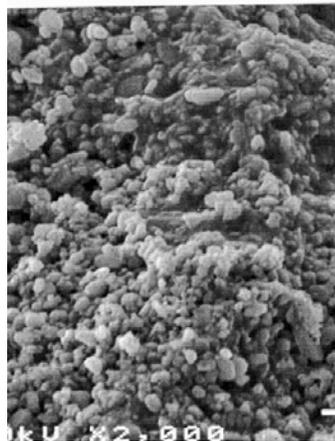
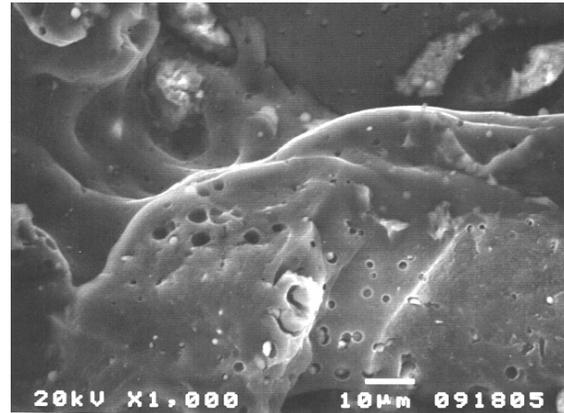


Fig. 1. Solubility vs. pH of several candidate oxides [5].



Ceramicrete  
 Ferrocement  
 Al-phosphate

Figure 2. Scanning electron micrographs of Ceramicrete, aluminum phosphate, and ferrocement [8-10].

Figure 3. Range of applicability of CBPCs and cement.