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Waste Materials in Construction: Putting Theory into Practice

Acid Resistance of Different Monolithic Binders and Solidified Wastes

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Abstract

Laboratory tests which add acid to a ground solidified product are useful for examining acid neutralizing capacity and dissolution of metals as a function of pH, but do not examine the effect of acid on the monolithic structure of the cement-based matrix, which is also important for reducing leachability of contaminants. In this study, specimens of five different cementing systems (portland cement, portland cement with silica fume, alkali-activated ground blast furnace slag, coal fly ash with lime, and high alumina cement with lime and gypsum), with and without waste addition, were immersed in three types of acid (pH 3 nitric acid, pH 3 acetic acid and pH 5 acetic acid) to investigate the effects of acid attack on a monolithic matrix. It was found that calcium silicate hydrate-based formulations with a low Ca/Si ratio have the greatest acid resistance. Acid resistance of sulphated high alumina cement specimens was poor.

1. INTRODUCTION

Recent results from a field study show that diffusion-limited release of alkalinity is an important control on leachability of metals from wastes treated by solidification with cement binders (Stegemann et al., 1996). The initial porewater pH of a cement-based solidified waste is typically higher than 12, resulting in high solubility and leachability of amphoteric metal contaminants. In the disposal environment, acidic or neutral conditions in contact with the solidified waste will deplete the excess lime and soluble alkalis which cause this high alkalinity and high leachability. Depending on the nature of the hydration products composing the solidified waste matrix, incongruent dissolution can lead to formation of a less alkaline to acidic outer "leached layer" on the surface of a monolithic solidified waste, enclosing an inner zone of higher alkalinity. The formation of this leached layer in portland cement-based matrices has been demonstrated by several authors (as summarized by Hinsenveld and Bishop, 1996). The pH of the leached layer will range from that of the inner zone to that of the surrounding environment, and will necessarily include a zone with pH 10 to 12, where the solubility of amphoteric metal contaminants will be low, resulting in secondary precipitation of metals diffusing outward from the highly alkaline inner zone (as well as inward from more acidic zones). Alkalinity from the interior of the monolith will replenish the leached layer by diffusion so that this mechanism for capture of amphoteric heavy metals remains active.

In addition to ensuring the controlled release of alkalinity important for immobilization of amphoteric heavy metals, the monolithic structure of a solidified waste limits the surface area of contact between groundwater and all contaminants, including organic compounds and anions, so that leaching of all contaminants is controlled by diffusion rather than advection.

By contrast, in a non-monolithic solidified waste, uncontrolled contact between the waste and acidic or neutral groundwater will result in an extended period of high alkalinity and high leachability, without the benefit of the leached layer contaminant capture mechanism. Although, depending on the solidified waste composition, an optimal pH environment for precipitation of amphoteric metals may be established over time, the extension of the period of high leachability will by then have resulted in transport of a much higher fraction of contaminants into the environment. Also, because leachant transport will be by more rapid advection rather than by diffusion, there will be increased contact with acidifying or neutralizing influences in a non-monolithic waste and the pH will drop below the optimal range for metals precipitation more rapidly than in a monolithic waste.

Thus, the monolithic structure of a solidified waste has important benefits for minimizing release of contaminants into the environment, which an equally alkaline non-monolithic material can not provide.

Typical properties which are measured to assess the durability of the monolithic structure of a solidified waste are: unconfined compressive strength, and freeze/thaw, wet/dry and biological weathering resistance (e.g., Wastewater Technology Centre, 1991, United States Environmental Protection Agency, 1993). Maintenance of an appropriate pH has long been recognized as being critical for precipitation of metals, but acid resistance is also an important aspect of the matrix durability of a monolithic solidified waste. Resistance of a cement-based matrix to acid attack will depend not only on the ability of the matrix components to neutralize acid, but also on the matrix microstructure, which determines the surface area in contact with acid, and the characteristics of the degradation products from acid attack, which may form a protective surface layer (Pavlik, 1994).

The response of different solidified waste matrix components to acid addition was the subject of previous work (Stegemann et al., 1994), which included a review of the chemical stability of cement hydration products over a range of pHs. This aspect of acid resistance was explored experimentally by using different binders to create a range of solidified products with different hydration products, and measuring their acid neutralization capacity and dissolution in a series of batch extractions of ground samples (<0.2 mm) with increasing amounts of nitric acid (Stegemann and Cote, 1991). The present work undertakes to examine and compare the effect of acid on the physical structure of different matrices by measuring the rate of corrosion of monolithic specimens of the same solidified products upon immersion in acid.

2. METHODS AND MATERIALS

2.1. Preparation of Monolithic Specimens

Five different solidification binders, representing different hydration products, were chosen for this work. The binders were: portland cement , portland cement with silica fume, alkali-activated ground blast furnace slag, coal fly ash with lime, and high alumina cement with lime and gypsum. The formulations were identical to those used in the previous study of acid neutralization capacity of ground solidified products, and are summarized in Table 1. The different binder systems have been numbered from 1 through 5, and a "W" indicates the batches containing waste.

Binders 1 to 4 were chosen to allow comparison between the corrosion resistance of portland cement, and blended cements containing industrial by-products. These four systems also have different Ca/Si ratios (shown in the last row of Table 1). Binders 1, 2 and 4 were used to solidify a plating sludge containing heavy metals; the set of binder 3 (activated blast furnace slag) was inhibited by the plating sludge in previous trials, so it was not suitable for testing as a monolith.

Binder 5 was selected to produce a high proportion of ettringite ($3CaO.Al_2O_3.3CaSO_4.32H_2O$) upon hydration, and was used to solidify a hazardous waste incinerator ash containing high levels of chloride and sulphate. The proportion of hydrated lime to high alumina cement was increased and gypsum was omitted in solidification of the ash, to allow the sulphate and chloride from the ash to form ettringite and calcium chloroaluminate ($3CaO.Al_2O_3.CaCl_2.10H_2O$).

Table 1. Formulations for monolithic specimens subjected to acid attack

	Percentage in batch (based on dry weight)								
Component	1	1W	2	2W	3	4	4W	5	5W
Portland cement	100	40	80	32	-	-	-	-	-
Silica fume	-	-	20	8	-	-	-	-	-
Blast furnace slag	-	-	-	-	92.5	-	-	-	-
Sodium metasilicate	-	-	-	-	7.5	-	-	-	-
Class F coal fly ash	-	-	-	-	-	80	48	-	-
High calcium hydrated lime	-	-	-	-	-	20	12	10	10
High alumina cement	-	-	-	-	-	-	-	60	30
Gypsum	-	-	-	-	-	-	-	30	-
Metal plating sludge	-	60	-	60	-	-	40	-	-
Hazardous waste ash	-	-	-	-	-	-	-	-	60
Water	40	50	40	50	40	40	50	40	50
Ca/Si mole ratio	3	3	1.4	1.4	0.5	0.5	0.5	-	-

All batches without waste were prepared at a water to cement ratio of 0.4, whereas a water to solid ratio of 0.5 was required in solidification of the waste.

Monolithic specimens were cast in clear polystyrene 4.5 cm diameter x 7.4 cm high right circular cylinder moulds. Samples were moist cured at 22°C for one year prior to testing.

2.2. Corrosion Experiments

Prior to exposure to an acidic environment, each monolithic specimen was saturated and cemented into its polystyrene mould using epoxy glue such that only one end of the cylinder was exposed. A thus partially enclosed monolithic specimen of each formulation was suspended with the exposed surface facing downwards in 1 L of three types of acid solution:

1) Nitric acid, continuously adjusted to a target pH of 3. Nitric acid, HNO_3, was chosen because it is a strong mineral acid which dissociates completely, whose salts are soluble. It has been used in previous work for measurement of acid neutralization capacity of ground samples,
2) Acetic acid, continuously adjusted to a target pH of 3. Acetic acid, CH_3COOH, is a weak organic acid (K_a at 25°C = 1.8×10^{-5}) which is often used in laboratory tests such as the USEPA Toxicity Characteristic Leaching Procedure to represent organic acids produced by decay of organic matter in landfills, and
3) Acetic acid, continuously adjusted to a target pH of 5, to provide a less aggressive comparison to acetic acid at pH 3.

The nitric acid solution had an initial pH of 3, i.e., a concentration of 1 mmol/L; the acetic acid solutions had initial pHs of 3 and 5, corresponding to concentrations of approximately 56 and 0.0056 mmol/L, respectively. The pH of all three series of experiments was manually monitored and corrected to pH 3 or 5, by addition of more concentrated nitric or acetic acid, as appropriate. This method of pH adjustment had the effect of substantially increasing ionic strength, and particularly nitrate or acetate concentrations, over the course of the experiment. For most specimens, the acid leachant was changed once or twice because of volume increase and algal growth, which returned the nitrate or acetate concentrations to their initial values.

The depth of complete disintegration of the matrix from the end of each cylinder and acid consumption were measured and recorded over immersion periods of up to 19 months. The precision and accuracy of the measurements was about 0.5 mm.

3. RESULTS AND DISCUSSION

In practice, the high alkalinity of the cement-based matrices made the target pH of 3 difficult to maintain, and the average pH measured for both the "pH 3" nitric and acetic acid solutions was actually 3.7, ranging from as high as 10.8 at the beginning of the experiment, to lower than 3 immediately after addition of acid. A target pH of 5 was maintained easily, although measured pH values did range between 11.5 at the beginning of the experiment and 3.4, immediately after acid addition. For the sake of simplicity, the acid solutions will be referred to by their target pHs in the following discussion.

The results from the acid attack by pH 3 nitric acid, pH 3 acetic acid, and pH 5 acetic acid are shown in Figures 1, 2 and 3, respectively, as plots of corroded depth (primary vertical axis) as a function of time (horizontal axis). Each figure shows five separate charts, one for each binder type, with results plotted for specimens with and without waste. The amount of acid added in order to maintain the target pH has also been plotted as a function of time, with reference to a secondary vertical axis on the right side of each plot. In comparing the plots, it should be noted that the time scale in Figures 1 and 3 ranges from 0 to 600 days, but in Figure 2 it ranges from 0 to 100 days. On the "corroded depth" axes, scales of 0 to 12 mm, or 0 to 120 mm were used, depending on the requirements; the scale for mmoles of acid addition was adjusted as needed to display the data.

3.1. Corrosion by pH 3 Nitric Acid

Figure 1 shows that 19 months of immersion in pH 3 nitric acid resulted in corroded depths of less than 2 mm for all the binders tested, with the exception of the high alumina cement/gypsum system assumed to have formed an ettringite matrix. Addition of plating sludge did not appear to negatively affect the acid corrosion resistance of portland cement products, with or without silica fume. These results are consistent with an observed decrease in solubility of the portland cement and portland cement/silica fume formulations containing plating sludge in previous acid neutralization capacity experiments on ground products (Stegemann et al., 1994). However, addition of plating sludge resulted in greater corrosion of the monolithic fly ash/lime product, which also crumbled at the cylinder edges, as well as showing increased corrosion over the exposed face. While strength development in this system was indicative of successful hydration, the waste appears to have changed the hydration products, as was also suggested by the absence of a calcium silicate hydrate (CSH) plateau in the acid neutralization capacity curve found in previous work.

After an initial lag period of low corrosion, the high ettringite binder was rapidly destroyed in less than 6 months; replacement of gypsum with incinerator ash resulted in even more rapid deterioration in only 4 months.

3.2. Corrosion by pH 3 Acetic Acid

Because acetic acid is a weak acid, a much higher concentration was required to achieve pH 3, than for the nitric acid. Consequently, immersion in pH 3 acetic acid (Figure 2) was much more aggressive than pH 3 nitric acid to all formulations. The pure portland cement formulation was initially corroded by the acid, and then turned salmon-coloured and expanded dramatically, cracking its mould. It is thought that the expansion was caused by reaction of the acetic acid with the free lime from the portland cement to form calcium diacetate. Calcium diacetate, $Ca(CH_3COO)_2.2H_2O$, has a high solubility ($K_{sp} \approx 6$), but the high concentration of acetate (up to 10 moles/L, because of the continual pH correction of the leachate) was sufficient to force it out of

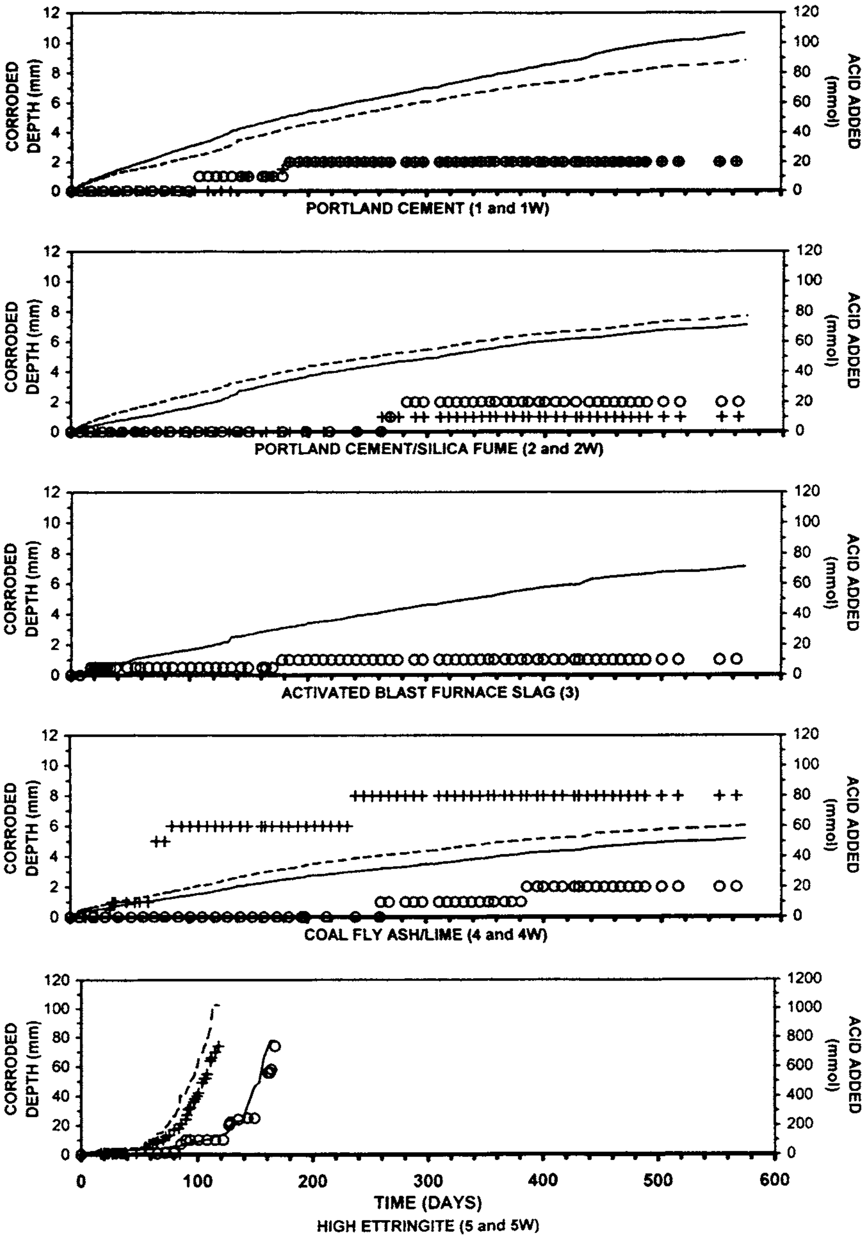


Figure 1. pH 3 nitric acid:
corroded depth (O no waste, + with waste) and
acid added (—— no waste,----- with waste)

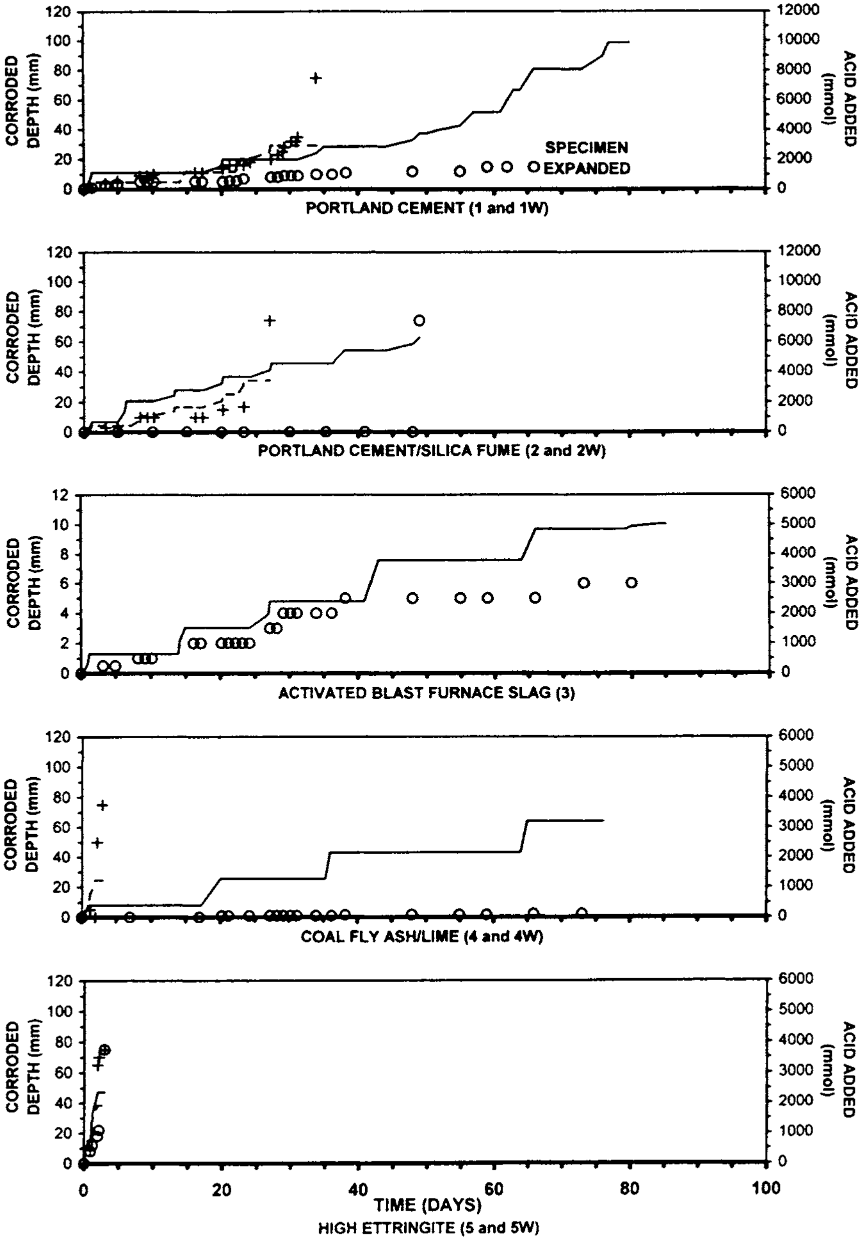
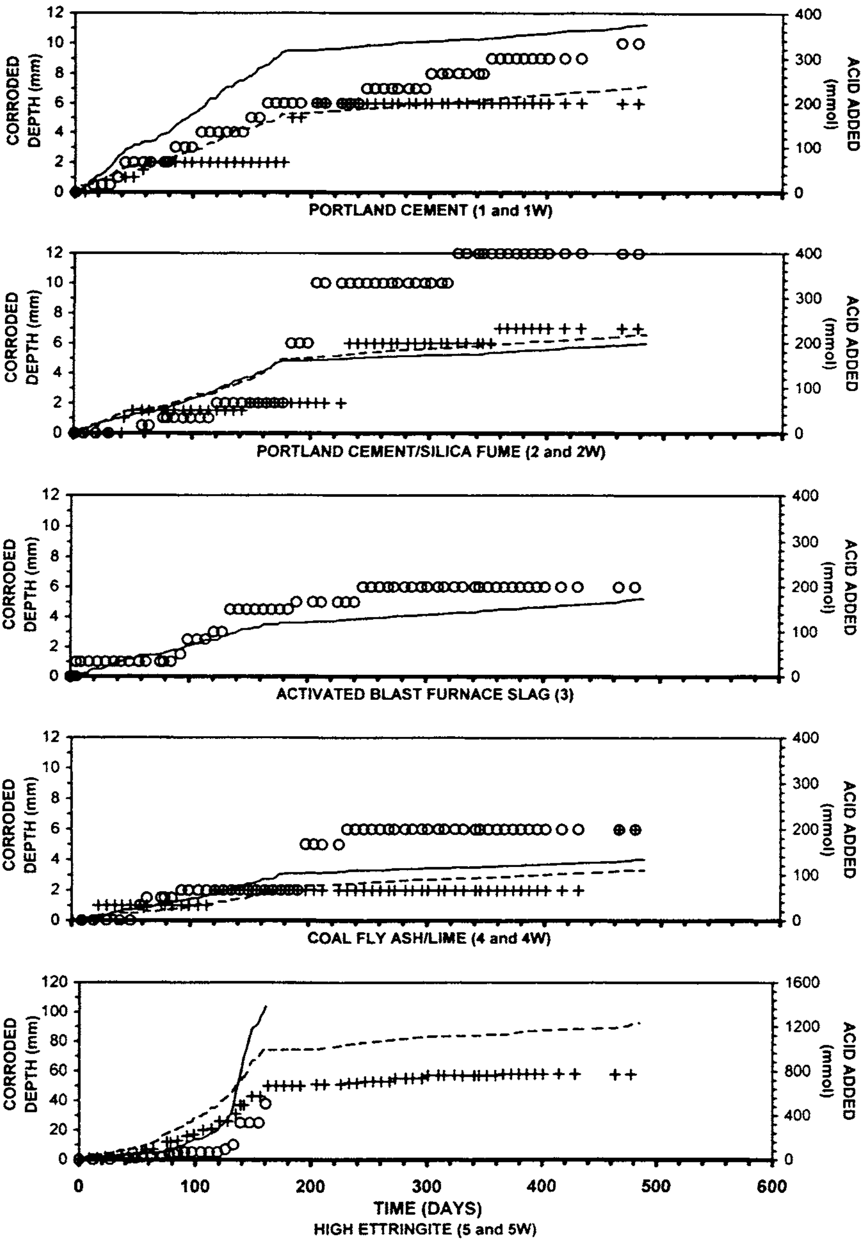


Figure 2. pH 3 acetic acid:
corroded depth (O no waste, + with waste) and
acid added (— no waste, ----- with waste)


PORTLAND CEMENT (1 and 1W)

PORTLAND CEMENT/SILICA FUME (2 and 2W)

ACTIVATED BLAST FURNACE SLAG (3)

COAL FLY ASH/LIME (4 and 4W)

HIGH ETTRINGITE (5 and 5W)

Figure 3. pH 5 acetic acid:
corroded depth (O no waste, + with waste) and
acid added (— no waste, ----- with waste)

solution. An orange colour was also observed in the outer layer of the portland cement formulation suspended in nitric acid. Other authors attributed an orange colour change observed for portland cement-based solidified wastes immersed in acetic acid to oxidized iron (Cheng and Bishop, 1996a). This explanation is consistent with the absence of a colour change in the specimens not containing portland cement.

Addition of silica fume consumed the excess calcium hydroxide generated by the portland cement, but the portland cement/silica fume specimen crumbled suddenly and completely, after exhibiting no corrosion for 7 weeks, suggesting that expansion reactions as well as acid attack may have affected its structural integrity. Calcium depleted from the calcium-rich CSH of this formulation may have reacted with the acetate to cause this effect. The portland cement and portland cement/silica fume specimens containing waste did not suffer any noticeable expansion, and were gradually but quickly corroded.

The activated blast furnace slag and fly ash/lime binders had not yet disintegrated when the experiment was discontinued after 80 days, but exhibited corrosion depths of 6 and 2 mm, respectively. Expansion did not appear to occur in these binders, and may have been averted by the lack of easily soluble calcium, as the Ca/Si ratio of these systems was 0.5. Addition of waste to the fly ash/lime system resulted in its complete disintegration within a week, showing again that the modified hydration products in this formulation had a poor acid resistance. The high alumina cement formulations also disintegrated within a week, due to the high solubility of ettringite and calcium chloroaluminate at low pH.

3.3 Corrosion by pH 5 Acetic Acid

Comparison of Figures 1 and 3 shows that pH 5 acetic acid was also more aggressive than pH 3 nitric acid, to all but the fly ash/lime/waste formulation and the high alumina cement formulations, with corroded depths between 6 and 12 mm measured after 16 months of immersion. It is possible that the deterioration of specimens in this experiment was due to a combination of acid attack and expansion. Because of the lower concentration of acetic acid, a different mechanism occurred than in the pH 3 acetic acid experiments; rather than causing massive expansion and failure, formation of smaller amounts of calcium diacetate lead to cracking at a smaller scale which facilitated acid attack. Specimens with less soluble calcium, i.e., with a lower Ca/Si ratio binder (activated blast furnace slag and fly ash/lime) and/or containing waste, were not as subject to expansion and therefore deteriorated less.

The high alumina cement specimens containing incinerator ash immersed in pH 5 acetic acid were the only ones of this binder type which had not completely corroded by the end of the test. A sharp discontinuity is apparent in the corrosion and acid addition curves after 22 weeks, which may be indicative of formation of a protective layer of aluminum triacetate and/or calcium diacetate by reaction of the acetic acid with aluminum and calcium liberated by ettringite and calcium chloroaluminate dissolution. This protective layer may not have had an opportunity to form at pH 3, because of the extreme rapidity of dissolution of the specimens. The discontinuity in the corrosion and acid addition curves for the remaining specimens after 25 weeks corresponds to a replacement of the leachant, and is unlikely to be related to calcium diacetate precipitation, as the amount of acetate added was insufficient to exceed solubility limits. For the same reason, formation of a calcium diacetate precipitate under natural conditions is unlikely.

3.4. Generalized Factors in Acid Attack

In general, the corrosion plots exhibited three stages: (1) a lag period before (2) acceleration of deterioration, followed by (3) a decrease in rate of deterioration.

It is postulated that the lag period is attributable to depletion of easily soluble alkalinity from the surface layer of the specimens, which resulted in consumption of acid, but left a structurally stable matrix. In the case of the portland cement formulations the soluble alkalinity was initially likely to have been mainly sodium, potassium and free lime; later on, once the pH of the corroding surface layer dropped below 12.5, and for the lower Ca/Si ratio products and those containing waste, it is expected that decalcification of calcium silicate hydrate (CSH) took place. For the CSH-based matrices, visible deterioration of the matrix structure would not be expected until the pH of the corroding layer decreased below 9.9, where CSH coexists with more soluble silica gel (see review in Stegemann et al., 1994). The lag period was longer for the lower Ca/Si ratio solidified products because the higher Ca/Si ratio products contained free lime. Free lime is more soluble than CSH, and leaves a higher porosity matrix as it dissolves, increasing exposure to acid attack. Cheng and Bishop (1996b) found a porosity of 0.8 in the decalcified layer of portland cement-based solidified wastes. For the high alumina cement formulations, the lag period may have been caused by dissolution of alkalis and free lime; deterioriation of the matrix structure would be anticipated to start when the pH of the surface layer dropped below approximately 11 (see review in Stegemann et al., 1994).

The period of accelerated corrosion was linear as a function of time. In the case of the CSH-based matrices, it resulted from increased dissolution of the silica-rich CSH, aluminosilicates and silica gel remaining after decalcification of the CSH, as the pH of the corroded layer dropped from 9 to below 5. Again, a higher Ca/Si ratio increased the vulnerability to acid attack in all three series of experiments. The corrosion rate was highest for the high alumina cement matrices, in which ettringite or calcium chloroaluminate dissolved rapidly.

In the portland cement and portland cement/silica fume systems, with and without waste, and in the activated blast furnace slag and fly ash/lime systems, it is postulated that a protective surface layer consisting mainly of silica gel, and also containing alumina and iron compounds, gradually developed over time. Further leaching of alkalis and calcium and inward movement of acid to the corrosion front then became controlled by diffusion through this layer (Pavlik, 1994). The benefit of the silica gel protective layer was most evident in the relatively low corrosion of the activated blast furnace slag and fly ash/lime specimens upon immersion in pH 3 acetic acid. The low free lime content of these matrices resulted in a particularly dense silica gel protective layer. This layer has an additional benefit in solidified wastes, in that the silica gel can adsorb heavy metal contaminants at pH values as low as 5 (Schindler et al., 1976).

A high proportion of free lime, or other soluble calcium, such as ettringite, can result in secondary precipitation of calcium salts, which may contribute to formation of a protective layer but can also lead to expansion, as was seen in the acetic acid experiments.

The corrosion rate did not decrease over time for any of the high alumina cement specimens, except the one made with incinerator ash and immersed in pH 5 acetic acid discussed in 3.3, as dissolution of the ettringite and/or calcium chloroaluminate matrices in nitric acid was complete, leaving no residue nor depositing a protective layer on the surface of the monolith.

Other authors have found that, at the same concentration, mineral acids are more corrosive to cements than weak acids (Pavlik, 1994 and Bayoux et al., 1990). Such was not the case in this series of experiments, because continued addition of acetate caused precipitation and expansion reactions which lead to increased matrix deterioration in the weak acid.

3.5. Acid Consumption of Different Matrices

A straight line relationship between depth of corrosion and acid addition would be expected for matrix deterioration by chemical dissolution. Plots of the depth of corrosion as a function of the amount of acid added are not shown here, but a straight line passing through the origin was fitted to the data for each specimen by the method of least squares, to determine slopes of mm of corroded depth per mmole of acid added. For the pH 3 nitric acid and pH 5 acetic acid experiments, most correlation coefficients (R) were found to be between 0.8 and 1, indicating that the corrosion depth and acid addition data were highly correlated, except when the corroded depth was too small to be accurately measured (e.g., activated blast furnace slag corroded by nitric acid), or when deterioration mechanisms other than dissolution were a factor (e.g., fly ash/lime/waste formulation in nitric acid). For the pH 3 acetic acid data, correlation coefficients higher than 0.8 were determined only for the blast furnace slag and fly/ash lime systems. These formulations were the only ones which maintained their structural integrity in the pH 3 acetic acid; under aggressive attack by acetic acid other deterioration mechanisms, e.g., expansion, cracking and crumbling, came into play for the other formulations.

For comparison with acid neutralization capacities measured for ground samples (Stegemann et al., 1994), the mm of corroded depth per mmole of acid added were converted to mmoles of acid added per gram of dry cement using the surface area exposed to the acid, and the solidified product densities and cement contents. Table 2 summarizes the resulting values for each specimen. The approximate amount of acid per gram of dry cement in the formulation, which was required to achieve complete matrix destruction, was read from the acid neutralization capacity (ANC) curves generated previously. It was assumed that the all matrices were completely destroyed at pH 5.

Table 2. Amount of acid required for complete matrix destruction

mmol of acid/ g of dry cement	Batch								
	1	1W	2	2W	3	4	4W	5	5W
pH 3 HNO_3	19	62	16	47	25	17	7.0	7.0	8.9
pH 3 CH_3COOH	160	160	**	55	360	800	41	39	20
pH 5 CH_3COOH	21	64	9.0	22	12	12	43	21	11
ANC to pH 5*	>17	23	16	20	13	5.0	11	8.0	6.4

* based on Stegemann et al., 1994

** slope not calculable because sudden crumbling followed a period of no corrosion

Values for which the correlation between corrosion depth and acid addition was poor (i.e., R<0.8) are shaded.

While the precision and accuracy of the slopes is not high, because of low precision of the depth measurement relative to the depth of corrosion, and poor correlation between the data for some specimens, it is possible to make some general observations:

Most obviously, the amount of acetic acid consumed at pH 3 was far greater than the acid neutralization capacity to pH 5 found previously. This is a consequence of the method of acid replenishment in this experiment, which resulted in buildup of large acetate concentrations, creating a buffer system which also consumed acid. This effect is not noticeable for the pH 3 acetic acid experiments, which had lower acetate concentrations, except for the high ettringite batches.

For the portland cement/silica fume formulation in pH 5 acetic acid it appears that significantly less acid was required for monolithic matrix dissolution than predicted by the acid neutralization capacity to pH 5. This may be explained by matrix deterioration through mechanisms other than dissolution, as discussed earlier. For most specimens, however, the amount of acid required for dissolution of the monolithic matrix was similar to or greater than that predicted by the acid neutralization capacity of ground solidified products to pH 5. Lower Ca/Si ratio monolithic products seem to have a higher acid resistance than might be expected solely based on the ANC to pH 5, which may be because of formation of a denser, less soluble silica gel at low pH. Unfortunately, there is insufficient data to statistically confirm this finding.

It also appears that the portland cement and portland cement/silica fume batches with waste consumed more acid before dissolving than those without waste, and that this effect was greater for the monolithic specimens than it was for the ground solidified product. It seems that the waste acted as an aggregate in the CSH matrix which decreased physical deterioration. This phenomenon was also observed for the fly ash/lime formulation in acetic acid.

4. CONCLUSIONS

The stages leading to deterioration of monolithic cement-based binders and solidified products under acidic conditions can be conceptualized as follows: 1) neutralization of soluble alkalis such as sodium and potassium from the surface, 2) dissolution of soluble alkalinity, such as free lime and ettringite from the surface, 3) formation of a protective surface layer of decalcified CSH and silica gel containing iron and aluminum silicates, and 4) diffusion control of continued neutralization of the alkalinity from the interior of the monolith through the surface layer. The decalcified CSH and silica gel surface layer is capable of adsorbing metals at pH values down to 5. Because stages 1 and 2 occur relatively rapidly, monolithic products which do not contain CSH (e.g., high ettringite formulations) are at a serious disadvantage because they simply continue to dissolve rapidly, do not form a protective surface layer of silica gel and therefore also have no capacity to retain metals at lower pH values. Formation of secondary precipitates by reaction of matrix dissolution products (e.g. calcium) with the the acid may be a complicating factor which can result in enhancement of the protective layer, or accelerated deterioriation.

Although information about acid neutralization capacity is a great help in interpreting data from acid attack experiments on monolithic binders and solidified products, it is not by itself a good predictor of the acid resistance of monolithic products. Whereas formulations containing portland cement generally have the highest acid neutralization capacity, CSH-based monolithic products with a lower Ca/Si ratio (e.g., activated blast furnace slag and fly ash/lime) exhibit greater acid resistance over time. The free lime in portland cement provides a high buffering capacity but is rapidly dissolved in acidic solutions, leaving a vulnerable porous silica-rich layer, whereas the CSH of lower Ca/Si ratio rapidly forms a dense silica-rich protective layer.

The addition of plating sludge to the binder systems was shown to change acid resistance. The acid resistance of the monolithic portland cement formulations containing waste (with and without silica fume) increased, compared to specimens not containing waste, but also compared to the ground material. The plating sludge appears to have acted as an aggregate which improved the durability of the matrix structure. The plating sludge interfered with formation of CSH in the activated blast furnace slag formulation, to the extent of inhibiting strength development, so that the product could not be tested as a monolith.

5. RECOMMENDATIONS

The focus on acid neutralization capacity of ground solidified products fails to recognize the contribution of the monolithic structure of a solidified product to immobilization of contaminants. For maximum acid resistance, design of solidification formulations should ensure formation of low Ca/Si ratio CSH.

Development of a standard test for measuring acid resistance of monolithic specimens should focus on minimizing potential complicating factors, such as secondary precipitation of reaction products of the acid and matrix. Ideally, automatic rather than manual pH adjustment to pH 5 with nitric acid is recommended for assessment of acid resistance of monolithic specimens. A less expensive alternative is to use pH 5 acetic acid with periodic leachant renewal, rather than pH adjustment.

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