EROSION OF A GEOPOLYMER

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ABSTRACT

Solid-particle erosion studies were conducted on a representative geopolymer. The test conditions were normal impact of 390-µm angular Al_2O_3 erodent particles moving at 50, 70, or 100 m/s. Steady-state erosion rates were obtained and the material-loss mechanism was studied by scanning electron microscopy. The geopolymer responded as a classic brittle material. Elastic-plastic indentation events led to formation of brittle cleavage cracks that resulted in spallation of material.   The erosion rate was proportional to erodent velocity to the 2.3 power. The erosion rate and mechanism for the geopolymer were nearly identical to what has been observed for erosion of Si single crystals.

Keywords: geopolymer, erosion, fracture

1. INTRODUCTION

Geopolymeric materials have been applied successfully to stabilization and solidification of many waste materials (Campbell *et al.*, 1987; Comrie, 1988; Davidovits *et al.*, 1990; Van Jaarsveld *et al.*, 1998 and 1999).   For encapsulation of heavy metals, however, most systems currently used are based on Portland cement (Hills *et al.*, 1993; Conner, 1993) or, in some cases, phosphate cements (Wagh *et al.*, 1999; Singh *et al.*, 1997). Depending on the product,

mechanical properties of the various final forms may be of concern. For example, abrasion, water-erosion, solid-particle-erosion, and fracture studies have been conducted on various Portland and phosphate cements (Fwa and Low, 1990; Momber and Kovaceviv, 1994; Goretta *et al.*, 1999a,b).

Geopolymers generally contain less porosity than cements, and superior mechanical properties may therefore be expected (Davidovits, 1991). We have previously subjected Portland and phosphate cements and many other engineering materials to erosion by streams of angular Al_2O_3 particles (Routbort, 1996). In this study, we have conducted identical tests on a representative geopolymer and then compared the resulting data set with those from other studies. The goal was to establish the extent to which geopolymers respond to erosion as do cements or conventional ceramics.

2.   EXPERIMENTAL PROCEDURES

2.1.   Geopolymer synthesis and specimen fabrication

[Grant to provide]

Densities were determined geometrically. The average specimen for strength testing was tested is the as-formed condition. Specimens for erosion testing were cut from the billet with a diamond-bladed saw. The average specimen for determination of erosion rate was ≈3 x 19 x 25 mm. No surfaces were polished. Smaller specimens were also prepared for study of individual impact sites (Routbort, 1996). These were polished with 1-µm diamond paste.

2.2.   Erosion testing

The curing strength of the geopolymer was monitored with a penetrometer. In addition, several cylinders were subjected to standard concrete compressive tests in a hydraulic press. The force was applied at a rate of 20 ± 2 MPa/min until the specimen failed.

Solid-particle erosion tests were carried out in a slinger-type apparatus that has been described previously (Routbort, 1996, and references therein). Tests were conducted in

vacuum (≈500 mTorr), and so aerodynamic effects were negligible. The feed rate of the erodent was ≈8 g/min. At such a slow rate, interactions between particles were also negligible. Consistent and reproducible measurements could therefore be made.

The erodent particles were angular Al_2O_3 abrasives (Norton Alundum 38) with mean diameter of 390 μm (Routbort, 1996). The particle velocity (V) was 50, 70, or 100 m/s and the angle of impact was 90°. All eroded surfaces were approximately 19 mm x 19 mm. Steady-state erosion rates (ER, in mg/g) were determined from plots of the specimen weight loss versus weight of particles impacting the surface. At least five runs were conducted for each specimen. To avoid possible problems due to environmental effects such as adsorption of water, each experiment to determine the ER values was completed in one day. Following each run, specimens were removed, brushed, cleaned by an air blast, and weighed. Each cycle of specimen removal through weighing took 14 ± 2 min. It is estimated that the average weight-loss measurements were accurate to ±5%. Uncertainties arose due to incomplete cleaning of the surfaces and slight adsorption of water.

Scanning electron microscopy (SEM) observations were made to correlate damage morphology of the eroded surfaces with the wight-loss and strength measurements. Single-impact damage sites were also examined by SEM.

3. RESULTS AND DISCUSSION

3.1. Geopolymer results

The geopolymer appeared to contain limited porosity. Its average density was 2.1 g/cm^3. Its average strength was 35 MPa, which is on the low side of what we typically produce.

Representative data for weight loss versus dose of impacting particles are shown in Fig. 1. ER was defined as the slope of the linear least-squares fit to the data. The scatter in the data for duplicate specimens tested at 70 and 100 m/s was probably more attributable to specimen differences than difficulty with making reproducible measurements. For example, two different heats of Ni metal, tested on our slinger apparatus 15 years apart, yielded ER values within less than 2% of each other.

Erosion rate versus velocity of impacting particles is shown in Fig. 2. For brittle materials, ER $\propto$ V^n, where the value of n depends on choice of model and shape of the impacting particle (Routbort, 1996). In the model of Weiderhorn and Lawn (1979), which is based on quasi-static impacts of sharp indenters, n = 2.4. For the geopolymer tested here, n = 2.3 $\pm$ 0.2, with the error bars comprising estimates of uncertainty inherent in making the measurements and the quality of the statistical fits to the data.
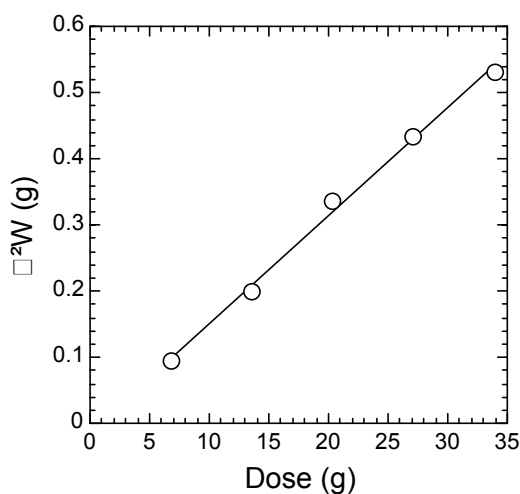

Figure 1: Weight loss vs. erodent dose for geopolymer impacted at 90° and 70 m/s.
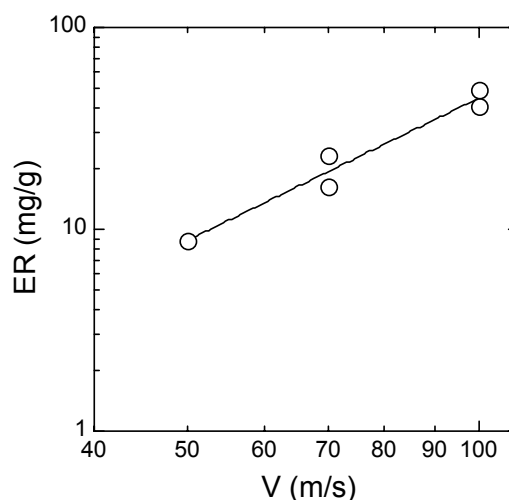
Figure 2: Steady-sate erosion rate vs. velocity for geopolymer impacted at 90°.

The data yielded consistent ER values and a dependence of ER on V as predicted by Weiderhorn and Lawn (1979). As such, the geopolymer appeared to respond as an ideal brittle material. SEM observations were also consistent with erosion of a classically brittle ceramic. In brittle solids, material loss induced by solid-particle impact is a sequential event. In brief: (1) Indentation creates an elastic-plastic zone beneath the impacting particle. (2) A radial crack perpendicular to the specimen surface is created beneath the elastic-plastic zone. (3) As the erodent particle recoils, a resulting tensile stress state induces formation of a lateral cracks approximately parallel to the surface. (4) The lateral cracks propagate to the surface and a chip spalls off.

The single-impact sites were characteristic of erosion of a brittle solid. Two basic types of events were observed. Some of the impacts evinced all of the features that lead to material

removal: indenting, radial-crack formation, and spalling caused by propagation of lateral cracks (Fig. 3a). Most impact sites were similar, but no lateral crack had propagated sufficiently to allow for removal of significant material (Fig. 3b). As expected, the size of the damage site scaled with velocity of impact. The microstructure between impact sites was dense and rather uniform, but contained many small cracks. These cracks may be responsible for the relatively low strength of the geopolymer.

Figure 3: SEM photomicrographs of normal-incidence single-impact sites in the geopolymer: (a) V = 50 m/s and (b) V = 100 m/s.

The steady-state erosion surfaces were as would be expected from the data and the single-impact observations. The surfaces were rough, and overlapping brittle cleavage fractures were evident. In addition, indentation events (Fig. 4a), which contained indications of plastic flow (Fig. 4b), were prevalent. Small pieces of Al_2O_3 were scattered over the surface eroded at 100 m/s, which indicates that the erodent fragmented to some extent during impact.

The dominant features that emerged during the SEM were the inherent uniformity and high density of the geopolymer and the large cleavage fractures that were induced during the steady-state erosion testing. Such large-scale fracturing is characteristic of materials of low fracture toughness.

Figure 4. SEM photomicrographs of geopolymer eroded into steady state at 100 m/s: (a) representative region, in which brittle fracture and indenting are observed, and (b) evidence for plastic flow within an indentation site.

3.2.   Comparison with other engineering materials

Our slinger apparatus for erosion testing has been used since 1975.   No significant modifications have been made.   Because test conditions have remained constant, direct comparisons of data sets are possible.   Comparisons with results from others can be made, but the conditions are almost never identical and so it can be difficult to draw unequivocal conclusions (Routbort and Scattergood, 1992).   We have therefore restricted our comparison of the erosion rate of the geopolymer to results from other materials tested on our apparatus. Materials that have been tested include metals, ceramics, cements, polymers, and composites. Data for a single set of conditions (erodent = 390-µm angular Al_2O_3, impact at 90°, V = 100 m/s) are displayed in Fig. 5.   The data are expressed as weight of material lost rather than volume of material lost.   Densities ranged from 1.33 g/cm^3 for the bismaleimide polymer (Brandstädter et al. (1991) to 7.93 g/cm^3 for the 304 stainless steel (Goretta et al. (1991).
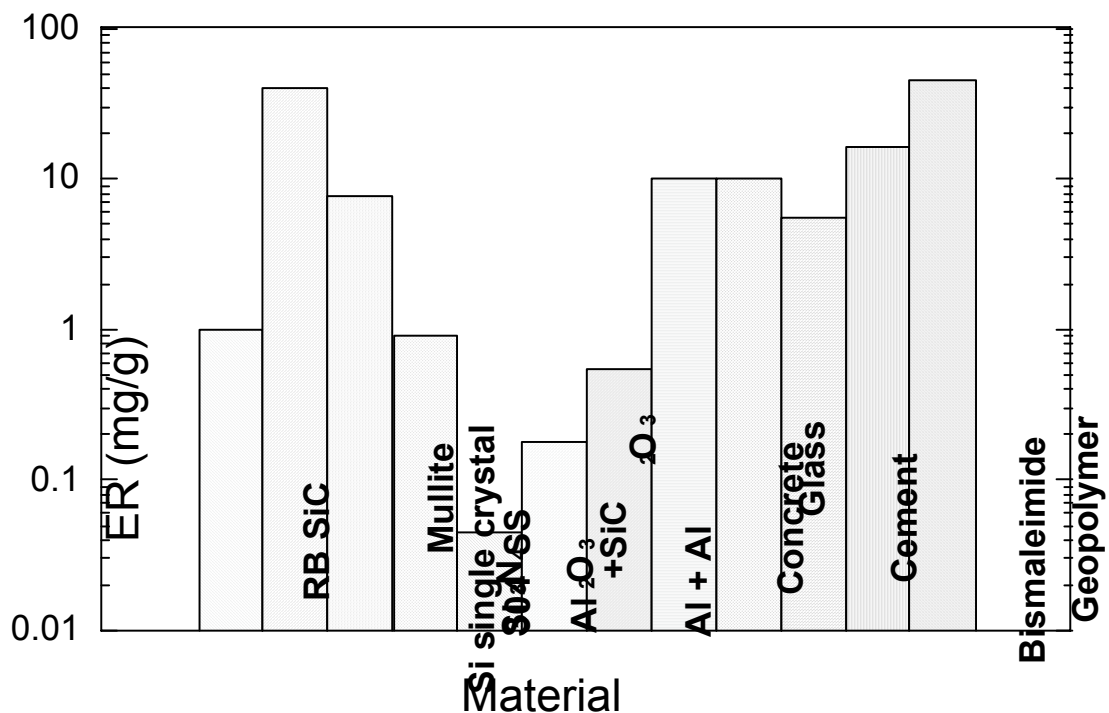

Figure 5:   Erosion rates of various engineering materials impacted at normal incidence by 390-µm angular particles with V = 100 m/s. Data taken from Routbort et al. (1980), Routbort and Scattergood (1980), Morrison et al. (1985), Morrison et al. (1986), Morrison et

al. (1987), Routbort *et al.* (1990), Goretta *et al.* (1999a), Brandstädter *et al.* (1991), and this study; in some cases, minor interpolation or extrapolation was required.

The erosion of the geopolymer was closest to that of Si single crystals. The erosion mechanism was probably closest as well. For both materials, classic brittle fracture occurred, with little of no evidence of a toughening mechanism mitigating the fracture. This result is mildly surprising. It offers testament to the relative density and phase purity of the geopolymer. It also provides guidance as to how erosion resistance can be improved, should that prove to be necessary. Geopolymers are simple and easy to produce and they readily lend themselves to incorporation into various composites. Such composites exhibit improved fracture toughness (Hammell *et al.*, 1998) and should prove to be more erosion resistant than an unreinforced geopolymer. Future work should include examination of the response of composite geopolymers to erosion.

The geopolymer is most similar to Portland cement in terms of synthesis and application. Although the erosion rate of Portland cement (Goretta *et al.*, 1999a) was similar to that of the geopolymer, the mechanisms were quite different. Whereas the geopolymer evinced material loss by classic brittle fracture, material loss in the Portland cement occurred by smaller-scale fractures coupled with effects of material degradation caused by loss of water. Local heating caused by the kinetic energy of the impacts induced the heating.

4. SUMMARY

Solid-particle erosion studies were conducted at normal incidence and 50-100 m/s on a representative geopolymer. The geopolymer responded as a classic brittle material. Elastic-plastic indentation events led to formation of brittle cleavage cracks that resulted in spallation of material. The erosion rate was proportional to erodent velocity to the 2.3 power, which is in agreement with predictions of Weiderhorn and Lawn (1979). The geopolymer exhibited evidence of low fracture toughness and thus relatively high erosion rate compared with other engineering materials.

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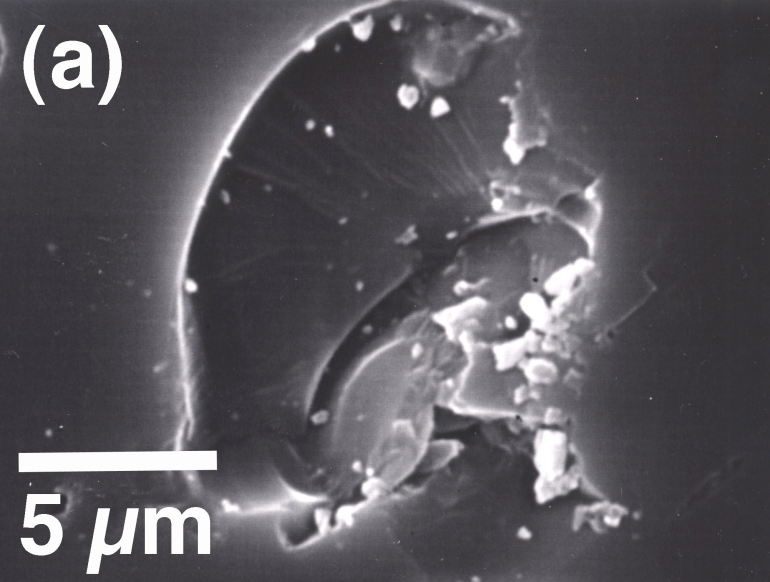
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(a)

5 μm

(b)

25 μm

(a)

25 μm

(b)

2 μm