

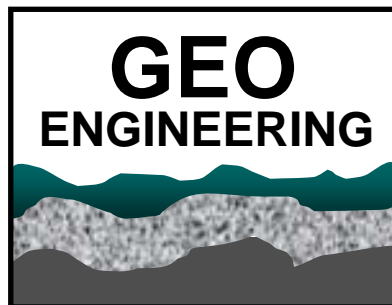
COPREX™ Column Treatability

Final Report

Geotechnics Laboratory Report

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I. Introduction

In the United States (U.S.), and in many industrialized countries, historical processing of chromite ore typically involved mixing dry-milled ore with lime (CaO) and soda ash (Na₂CO₃), followed by roasting at high temperatures to promote oxidation of the trivalent form of chromium within the ore. Chromium was then recovered (primarily in the form of soluble sodium chromate (Na₂CrO₄)) by countercurrent leaching processes. Chromium ore processing residue (COPR), the waste from processing chromite ore, contains approximately 2 to 7 percent chromium by weight owing to the incomplete oxidation of the ore and the incomplete leaching of sodium chromate. Millions of tons of waste COPR were produced in the U.S. Mid-Atlantic Region. This material was sold and/or given away as fill and/or construction aggregate for purposes such as backfill at demolition sites, grading for road construction, preparation for building foundations, sewer line construction, berms for storage tanks, wetland filling, and other construction and development projects (Burke et al., 1991; State of New Jersey, 2002). Highly alkaline COPR (typical soil pH > 11) leaches highly toxic hexavalent chromium (Cr(VI)) into local ground and surface waters. The impact of this leaching is dramatic. Leachate from COPR fills is not only phytotoxic, but also poses significant risks to the human population via dermal and inhalation exposure. Chromium is corrosive, allergenic, and mutagenic (Burke et al., 1991). Human studies have shown that hexavalent chromium is a human carcinogen, especially within the respiratory tract (USEPA, 1998).

REDOX SOLUTIONS, LLC (REDOX) has developed a reagent-based technology for the treatment of COPR. Internal research conducted by REDOX resulted in the identification of a chemical treatment process (COPREX™) capable of stabilizing alkaline COPR without pH modification. This treatment process reduced chromium Toxicity Characteristic Leaching Procedure (TCLP) leaching rates to levels below 0.1 mg/L. Significantly, this polysulfide-based reagent exhibited no increase in chromium over time, which is in stark contrast to the chromium rebound exhibited by competing reduction-based, pH control treatment chemistries. REDOX has developed a manufacturing process for the chemical reagent that significantly reduces the costs of production versus traditional manufacturing processes. However, the application has not, to date, been rigorously reviewed in a controlled laboratory setting in regards to the long-term leaching characteristics of COPREX-treated COPR. The purpose of this laboratory study conducted at the University of Wisconsin-Madison (UW-Madison) is to assess the long-term control of Cr(VI) leaching offered by COPREX™.

The objectives of the bench-scale COPREX™ column treatability study, as outlined in UW-Madison's February 02, 2005 research proposal, were

- To assess the long-term control Cr(VI) leaching offered by the COPREX™ reagent-based treatment process using synthetic precipitation as leaching solution

- To elucidate an understanding of the physical-chemical mechanisms of the treatment process that control the leaching of hexavalent chromium from the treated matrix in so far as possible
- To analyze the physical, mineralogical, and treatment permanence of the treated waste

To accomplish these objectives, a two-part laboratory study was undertaken. The first component was a column leaching experiment. Treated COPR was slurried into an instrumented column. After a 3-day saturation period, 20-plus pore volumes of flow (PVF) of synthetic rainwater permeant was sent through the column. This permeant represents the common endpoint expected for long-term, in situ flow conditions for material left on site after treatment. The leaching results from the COPREX-treated COPR are compared to a previously tested control column consisting of untreated COPR permeated by synthetic groundwater (for complete results, see Tinjum et al. (2005)). In addition to the mineralogical characterization of the COPREX residuals, physical parameters (e.g., dry unit weight, water content, and porosity) were determined prior to and after flow termination

The second component of the laboratory study focused on characterization of COPR in the pre- and post-treatment conditions. Specific characteristics of the waste material was determined by a variety of techniques, including determinations of specific gravity, grain-size distribution, and TCLP reference state; and mineralogical characterization by means of x-ray fluorescence (chemical composition), x-ray diffraction (crystalline phases present), and scanning electron microscopy (distribution of element concentrations across typical particles). These initial characterizations serve as a control to differentiate the post-test condition from the pre-test condition.

II. Materials and Methods

On a visual basis, the field-moist COPR used in this study was olive black in color, with sub-rounded, fine to medium sand-size particles. The COPR sample included trace amounts of coarse sand-size and fine gravel-size materials (partially a cemented conglomeration of medium-size grains and some molten material). The source of the COPR is a site in Hudson County, New Jersey.

The column test was conducted in an acrylic column (see Figure 1), with a diameter of 190 mm and height of 450 mm. Representatives from REDOX were present at UW-Madison's Geo Engineering Laboratory on March 31, 2005, to deliver the COPREX reagent and to assist in the mixing of the reagent with the COPR. Prior to treating the COPR, particles larger than 10 mm were removed. COPREX reagent was added to 14.65 kg of field-moist COPR, at a 10%, by weight, treatment dose. The reagent was mixed with the COPR using trowels for a period of approximately 5 min, placed in a sealed plastic bag, and allowed to hydrate for 24 h. The mixture was then placed in the column. Compaction and/or vibration techniques were not applied to the treated COPR within the column because of the high water content (26.5%) and slurry-like properties

of the mixture. The column was filled to a 275-mm height with the COPREX-treated COPR. The top of the column was not filled with solids to permit observations of swell and release of gases.

A portion of the treated solids were saved for TCLP analysis (EPA SW-846 1311), synthetic precipitation leaching procedure (SPLP) (EPA SW-846 1312), and leaching with a synthetic groundwater fluid (site specific groundwater chemistry for a COPR site in Maryland, with a groundwater pH of 12.0). For the SPLP analysis, the synthetic precipitation used was based on Standard Reference Material (SRM) 2694 (Koch, 1986) for a synthetic rainwater typical of locations east of the Mississippi River, with a pH of 4.3.

Influent synthetic rainwater was pumped into the columns at a rate of 1.5 mL/min, which corresponds to approximately one pore volume of flow (PVF) every 2 d. Composition of the synthetic rainwater was based on SRM 2694. Pore fluid and column effluent samples were immediately analyzed for pH and conductivity, filtered, and refrigerated. Cr(VI) concentrations were determined colorimetrically within 3 d of collection by reaction with 1,5-diphenylcarbazide in acid solution (EPA SW-846 7196A). The portion of the sample designated for metals analysis was acid preserved prior to analysis by inductively coupled plasma (ICP) (EPA SW-846 6010B). Bulk chemistry of column residuals was obtained by a combination of X-ray fluorescence (XRF), acid digestion (EPA SW-846 3050B), and alkaline digestion (EPA SW-846 3060A).

In preparation for mineral phase identification by X-ray powder diffraction (XRPD), specimens of air-dry COPR were ground with a mortar and pestle until the material passed a U.S. No. 200 sieve (75 μm). Approximately 2 g of the powder was then placed in an acrylic sample holder, with a specimen depth of 3 mm. Copper K_{α} radiation (wavelength, λ , = 1.54056 Å) was used by the diffracted beam monochromator. The X-ray analysis was conducted with beam energy of 40 keV and a current of 35 mA. Diffraction patterns were recorded by step scanning from 7.5° to 72.5°, with a step size of 0.01 and counting for 1 s per step.

In preparation for electron probe microanalysis (EPMA), COPR grains were impregnated with low-viscosity epoxy resin, followed by graduated polishing, and placement of a final coating consisting of a 20 nm layer of vacuum evaporated carbon. Where potential charging was of concern, the bulk soil specimen was coated with Au-Pd of 20-nm-thickness. Qualitative energy dispersive spectrometry (EDS) analyses were conducted with a Cameca SX50/51 (SN485), with beam energy of 15 keV and a current of 20 nA.

III. Results and Discussion

A. Physical and Mineralogical Characterization

1. Physical Parameters

The average specific gravity of the COPR used in this study was 2.96, which is within the expected specific gravity range for this source of COPR (2.72 to 2.99) as reported by Tinjum (2004). This range is similar to the range reported for Hudson County COPR (2.72 to 3.21, Meegoda et al., 1999). Water content of the COPR ranged from 19.8 to 21.2%.

Figure 2 shows the grain-size distribution result for the COPR used in this study. The COPR is a poorly-graded material according to Unified Soil Classification System (U.S.C.S.) (ASTM D-2487) criteria, with less than 2% fines (i.e., % passing the 75 μm sieve). The specimen divided nearly equally between fine and medium sand-size fractions. Because of the uniformity of the COPR evaluated, the poorly-graded particle distribution, and the visual observations, the COPR used in this study is likely from a 'pure' COPR source (i.e., one with minimal non-COPR fill material incorporated).

2. Chemical Composition

Results from the XRF analysis of the raw COPR are presented in the first row in Table 1. The elemental composition largely represents the raw input materials to the chromite ore manufacturing process: i.e., Al, Cr, Fe, and Mg from the raw ore $[(\text{Mg}^{2+}, \text{Fe}^{2+})\text{O} \cdot (\text{Cr}^{3+}, \text{Al}^{3+}, \text{Fe}^{3+})_2\text{O}_3]$; Ca from lime (CaO), quick lime $[\text{Ca}(\text{OH})_2]$, or limestone $[\text{Ca}(\text{CO}_3)]$; with the Na from the soda ash (Na_2CO_3) input mostly removed by leaching processes during processing or weathering. Because of the high percentage of calcium within the COPR, the manufacturing technique used to produce this COPR was likely the "high lime" process.

3. Mineralogical Composition

Brownmillerite ($\text{Ca}_2\text{Fe}_{2-x}\text{Al}_x\text{O}_5$) is the major mineral phase present in the untreated COPR sample. Figure 3 shows the XRPD patterns for scans conducted. Brownmillerite is positively identified by the characteristic double peak at 2.65 and 2.67 \AA (33.84° and 33.40°). In addition, when comparing the top 15 to 20 peaks in the XRPD patterns, the top 15 characteristic brownmillerite peaks are indexed. However, many of the characteristic peaks are broad – commonly with full-width half-maximum (FWHM) values in the range of 0.2° to 0.4° . These broad peaks are characteristic of a number of potential contributing factors, including small crystalline size, overlapping peaks, and chemical zonation.

The remaining crystalline phases in the untreated COPR include portlandite $[\text{Ca}(\text{OH})_2]$, calcite $[\text{Ca}(\text{CO}_3)]$, and possible trace amounts of chromatite $[\text{CaCrO}_4]$ and

hydrocalumite $[\text{Ca}_4(\text{Al,Fe})_2(\text{OH})_{12}\text{X}\cdot 6\text{H}_2\text{O}]$ where $\text{X} = (\text{OH})_2^{2-}$, SO_4^{2-} or CrO_4^{2-} . No amorphous phase is apparent in the untreated COPR. Various calcium-aluminate-silicate (CAS) cement phases appear to be present, possibly calcium aluminum oxide ($\text{Ca}_3\text{Al}_2\text{O}_6$). Other CAS phases would be expected, but may not exist in high enough concentrations to elucidate peaks. The absence of a phase, as determined by XRPD analyses, does not mean that the phase is not present. In general, the detection limit of crystalline phases by XRPD may be as high as 5% of the total specimen weight.

Qualitative X-ray mapping using a 1- μm grid was conducted on a polished, cross-sectioned COPR particle (Figure 4). In qualitative x-ray mapping, the lighter the image area, relatively, the higher the concentration (i.e., more x-ray counts specific to the energy level of the element portrayed). Black/dark areas indicate that the element is not present or at very low concentrations. Intensity levels shown are relative only to the particular element and cannot be directly correlated vis-à-vis to intensity maps of other elements (i.e., maps are qualitative, not quantitative). As expected based on the XRF bulk chemistry results, calcium is the dominant phase across the COPR grain. Calcium dominates within the brownmillerite structures, in addition to the interstitial areas where previously identified phases such as portlandite and CAS cement are likely. The only locations where Ca is not present are the relict chromite ore particles, which are readily identified as the bright areas in the chromium X-ray map. Relatively elevated Cr concentrations occur in reaction rims surrounding numerous sub-particle features. As shown in Figure 4, Fe is exclusively incorporated in the brownmillerite and chromite structures of COPR particles, with no accumulations in the interstitial regions. The bulk of the Al mass is also incorporated in the brownmillerite and chromite structures within the sub-particles; however, Al also coats the sub-particle surfaces in the interstitial regions, likely as accumulations of gibbsite and/or CAS cements. The X-ray maps show magnesium to be evenly distributed in small clusters throughout the COPR particle, whereas trace concentrations of Si exist within the brownmillerite structures and slight accumulations also coat the sub-particle outer surfaces.

B. Column Testing

1. Pre-test Conditions

At the start of the permeation period, the treated COPR had a dry unit weight of 15.7 kN/m^3 , an initial void ratio (e_0) of 0.85, and initial porosity (η_0) of 46% (see Table 2). The 15.7 kN/m^3 dry unit weight is similar to the unit weight observed for untreated COPR compacted at standard Proctor effort (ASTM D 698), but higher than the dry unit weight achieved during the preparation of a column of dry, uncompacted COPR (12.9 kN/m^3) previously tested at UW-Madison (Tinjum et al. 2005).

In addition to the column testing, the treated COPR was tested within 48 hours of mixing with a variety of synthetic leachates (TCLP, SPLP, and synthetic groundwater) in batch mode (i.e., end-over-end mixing for 18 hours at a liquid-to-solid ratio of 20:1). As shown on Table 3, regardless of synthetic leachate used, aqueous chromium levels

were below the detection limit of 0.33 mg/L. A TCLP Cr concentration > 5 mg/L categorizes the residuals as “characteristically hazardous;” thus, the COPREX-treated material classified as non-hazardous for Cr per the USEPA definition.

2. Flow-through Results

After a 3-d saturation period, synthetic rainwater was pumped through the column for a period equivalent to 23.5 PVF. One PVF corresponds to the volume of fluid equivalent to the total amount of voids in the column specimen (3,580 mL for the placement conditions of this experiment). Aqueous metal concentrations of the porewater collected from the upper and middle ports and the column effluent are graphed against PVF in Figure 5. Aqueous concentrations of Ca exhibit an immediate peak (1,100 mg/L for the effluent), followed by gradual tailing to final concentrations in the range of 200 to 400 mg/L, depending on the sampling location within the column. This Ca response is similar to that observed for a COPR-filled column permeated with synthetic groundwater (Tinjum et al., 2005) (see Figure 6), with the exception that the synthetic groundwater column exhibited a lower and delayed peak. The Ca concentrations in the COPREX column fluctuated more in the pore fluid collection ports than in the effluent, which showed the most consistent tailing trend.

In addition to Ca, aqueous concentrations of Mg were measured above the detection limits (DLs) in the treatment column. Na was also above the DL, but was a component of the treatment chemistry. Other than a few isolated hits of Cr_{total} (i.e., above the federal drinking water standard of 0.1 mg/L (US EPA, 2003)) within the porewater of the column (Figure 5d), Cr_{total} (including Cr(VI)) was not leached in the effluent through flow termination at 23.5 PVF. In comparison, for a synthetic groundwater control (Tinjum et al., 2005), Cr concentrations in the effluent held steady at 100 mg/L, even after 20 PVF. No significant deviations in the starting pH (approximately 12.0) were observed throughout the test period from any of the sampling ports (Figure 7a). The stable pH readings indicate that the reagent does not alter the pH condition of the treated COPR. In addition, conductivity stabilized to levels below 5 mS within 5 PVF (Figure 7b).

3. Column Residuals

Once the flow into the treatment column was terminated, the column was disassembled and physical and mineralogical testing was conducted on the residuals. Physical properties of the residuals are summarized in Table 2. The average dry unit weight of the column permeated with the COPREX reagent increased to a 16.4 kN/m^3 , the average specific gravity after testing of 2.88 was slightly lower than the pre-test specific gravity of 2.96, and the average porosity decreased to 42%. The changes in dry unit weight and porosity from pre-flow conditions are attributed to consolidation-induced settlement (45-mm change in solid height) of the slurry-like treated COPR and not to physical/mineralogical changes (e.g., precipitation within pore space).

Two specimens of column residuals were tested for residual Cr(VI) concentrations using alkaline digestions. While total Cr concentrations did not decrease from the pre-

test concentration (Table 1), the alkaline digestion results showed that < 10 mg/kg of the solid residuals were composed of Cr(VI) (i.e., < 0.001%). This concentration of Cr(VI) meets the strictest of the proposed New Jersey Department of Environmental Protection soil cleanup criteria for Cr(VI) of 20 mg/kg for the inhalation exposure pathway (NJDEP, 1998).

Qualitative X-ray mapping using a 4- μm grid was conducted on a polished, cross-sectioned COPR residual particle from the post-flow column (Figure 8). Calcium dominates within the brownmillerite structures, in addition to the interstitial areas where previously identified phases such as portlandite and CAS cement are likely. The bulk of the Al, Cr, and Fe masses are incorporated in the brownmillerite structures within the sub-particles. A lesser concentration of Cr is observed within the subparticle interstitial space, either due to actual lower concentration levels or because S masks the Cr response. An important observation is that S is evenly distributed throughout the interstitial region of the treated particle, even though the particle was part of the treated column residuals, which underwent 23.5 PVF. This indicated that the S component of the COPREX reagent survived the long-term flow period of this experiment. In addition, the even distribution indicates a homogeneous treatment of the particle and not a surficial treatment. However, the S compounds did not penetrate into the brownmillerite structure, which is not of concern as the brownmillerite structure contains Cr(III) and not Cr(VI). The X-ray maps show Mg to be evenly distributed in small clusters throughout the treated particle, whereas trace concentrations of silica exist within the brownmillerite structures and slight accumulations also coat the sub-particle outer surfaces.

For the column residuals analyzed for mineralogical phase identification by XRPD, (Figure 3), there are three significant peak changes when comparing a specimen of untreated COPR. There is an additional major peak at 8.5° that is not attributable to documented mineral phases in untreated COPR. The mineral phase associated with this peak may be darapskite $[\text{Na}_3(\text{SO}_4)(\text{NO}_3)\cdot\text{H}_2\text{O}]$, but secondary peaks expected for this mineral are not conclusive. The existence of this mineral phase is likely attributable to constituents of the COPREX reagent and not to secondary mineral precipitation from reaction with COPR minerals. A second significant peak difference is the increase in peak intensity at 11.6° , which corresponds to gypsum ($\text{CaSO}_4\cdot 2\text{H}_2\text{O}$) and/or hydrotalcite $[\text{Mg}_6\text{Al}_2(\text{CO}_3)(\text{OH})_{16}\cdot 4\text{H}_2\text{O}]$ mineral phases. The gypsum is likely a secondary mineral precipitation phase caused by reaction of free Ca with sulfate from the treatment reagent, while hydrotalcite is a hydration product of minerals within COPR. The third significant peak change is the increase in the 17.4° peak intensity, which is likely indicative of increased observable contributions from the hydrocalumite mineral. Hydrocalumite, similar to hydrotalcite, is a weathering/hydration product of brownmillerite.

4. Hydraulic Conductivity

Hydraulic conductivity was indirectly measured during the column experiment test by recording differences in piezometric levels over a set flow length. The hydraulic

conductivity relationship with PVF is shown in Figure 9. The hydraulic conductivity stabilized at a value of 1×10^{-6} m/s after approximately 10 PVF. This compares to an approximate hydraulic conductivity of 2×10^{-4} m/s for loosely-placed COPR permeated with synthetic groundwater (Tinjum et al., 2005). Thus, the hydraulic conductivity of the COPREX™-treated sample had almost a 2 order-of-magnitude decrease in hydraulic conductivity as compared to a loosely-placed COPR sample. The hydraulic conductivity increase for the COPREX treatment is attributed mostly to the increase in density of the treated COPR sample rather than precipitation or cementation phenomena.

IV. Conclusions and Recommendations

The results from the column test indicate that the COPR treated by the COPREX™ reagent was effective at eliminating the long-term leaching of Cr (hexavalent and trivalent) over a period covering at least 23.5 PVF, whereas Cr(VI) continued to be leached at high concentrations (i.e., > 50 mg/L) from a comparable synthetic groundwater column of untreated COPR (see Tinjum et al., 2005), even at 20 PVF. Treatment of the COPR by the COPREX™ reagent eliminated Cr leaching from the column without requiring or causing changes to the pH environment or significant changes to the mineralogical makeup of the COPR. In addition, residual levels of Cr(VI) in the column residuals were less than 10 mg/kg, which is less than the strictest NJDEP soil remediation goal of 20 mg/kg for the inhalation exposure route. The hydraulic conductivity of COPREX-treated COPR stabilized at 1×10^{-6} m/s, which is similar to a typical hydraulic conductivity value of silty, fine sand. Application of the reagent to COPR did not inhibit the hydraulic flow of synthetic precipitation through the treated matrix.

The major mineral phases of COPR remain relatively unchanged in pre- and post-treatment analyses. Major mineral phases, such as brownmillerite, portlandite, and calcite, are not significantly changed by the COPREX™ reagent. However, secondary precipitation of gypsum in the post-treatment residuals occurs in addition to an increase in XRPD peak intensities for weathering products, such as hydrocalumite and hydrotalcite. Of major significance, X-ray maps of a treated, residual particle demonstrate that sulfur compounds penetrate evenly and thoroughly into the interstitial region of the COPR particle. This penetration of the sulfur indicates that the treatment reagent penetrates deeply into COPR particles and thus offers more than a surficial treatment.

The initial testing of the COPREX™ reagent demonstrates a high level of promise for the treatment of COPR. Additional testing is recommended to continue to assess the long-term leaching characteristics of COPR treated by COPREX™, including dosage evaluations and field application studies. Objectives of a second phase of laboratory-scale testing would be to determine the reagent dosage requirements as a function of COPR type (e.g., coarse-grained versus fine-grained), chromium content (measured as the solid chromium oxide (Cr_2O_3) content), soil pH, bulk soil chemistry, and TCLP values. In addition, field application scenarios should be evaluated to

determine the feasibility and treatment effectiveness (on a laboratory scale) of applying the reagent in situ by means of common delivery techniques (such as infiltration galleries, soil mixing, and pressure injection)

V. References

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TABLES

Table 1. Bulk Chemistry of the Column Residuals.

Material	Oxide Percentages (by weight)							
	Al	Ca	Cr	Fe	Mg	Si	LOI	Total
<i>Untreated COPR</i>	10.31	36.32	3.71	19.28	9.33	6.53	12.35	99.37
Residuals from the Treatment Column								
Upper 1/3	10.78	35.05	3.58	18.21	8.19	4.57	14.30	96.10
Middle 1/3 (a)	10.95	35.14	3.61	18.52	8.38	4.57	12.45	95.11
Middle 1/3 (b)	10.84	35.25	3.68	18.54	8.27	4.40	12.50	95.01
Lower 1/3	10.89	35.05	3.64	18.63	8.35	4.43	12.35	94.84

Notes: LOI = Loss on Ignition
 Na₂O, K₂O, TiO₂, and MnO₂ all at values less than 1%.

Table 2. Physical Parameters of Treatment Column Residuals.

Layer	Dry Unit Weight (kN/m ³)	Specific Gravity	Porosity
Column Averages			
Test Start	15.7	2.96	0.460
Test End	16.4	2.88	0.420
(upper, mid, lower)	(14.9, 16.6, 17.3)	(2.90, 2.84, 2.91)	(0.476, 0.404, 0.394)
<i>Loosely placed, dry, untreated COPR</i>	13.5	2.95	0.536

Table 3. Batch Leaching Results

Material	TCLP Fluid (pH 2.88)				Syn. Rainwater (pH 4.3)				Syn. Groundwater (pH 12.0)			
	Final pH	ORP (mV)	Cr (mg/L)	Cr(VI) (mg/L)	Final pH	ORP (mV)	Cr (mg/L)	Cr(VI) (mg/L)	Final pH	ORP (mV)	Cr (mg/L)	Cr(VI) (mg/L)
COPR ⁽¹⁾	8.9	140	78	76								
COPREX-Treated ⁽²⁾	9.7	-510	<0.33	0.7 ⁽³⁾	12.1	-510	<0.33	4.8 ⁽³⁾	12.3	-510	<0.33	0.7 ⁽³⁾

Notes: ⁽¹⁾Air-dried prior to batch leaching.

⁽²⁾Batch leaching initiated within 1 h of treatment.

⁽³⁾False hit due to sulfide precipitation interference with colorimetric analysis.

FIGURES

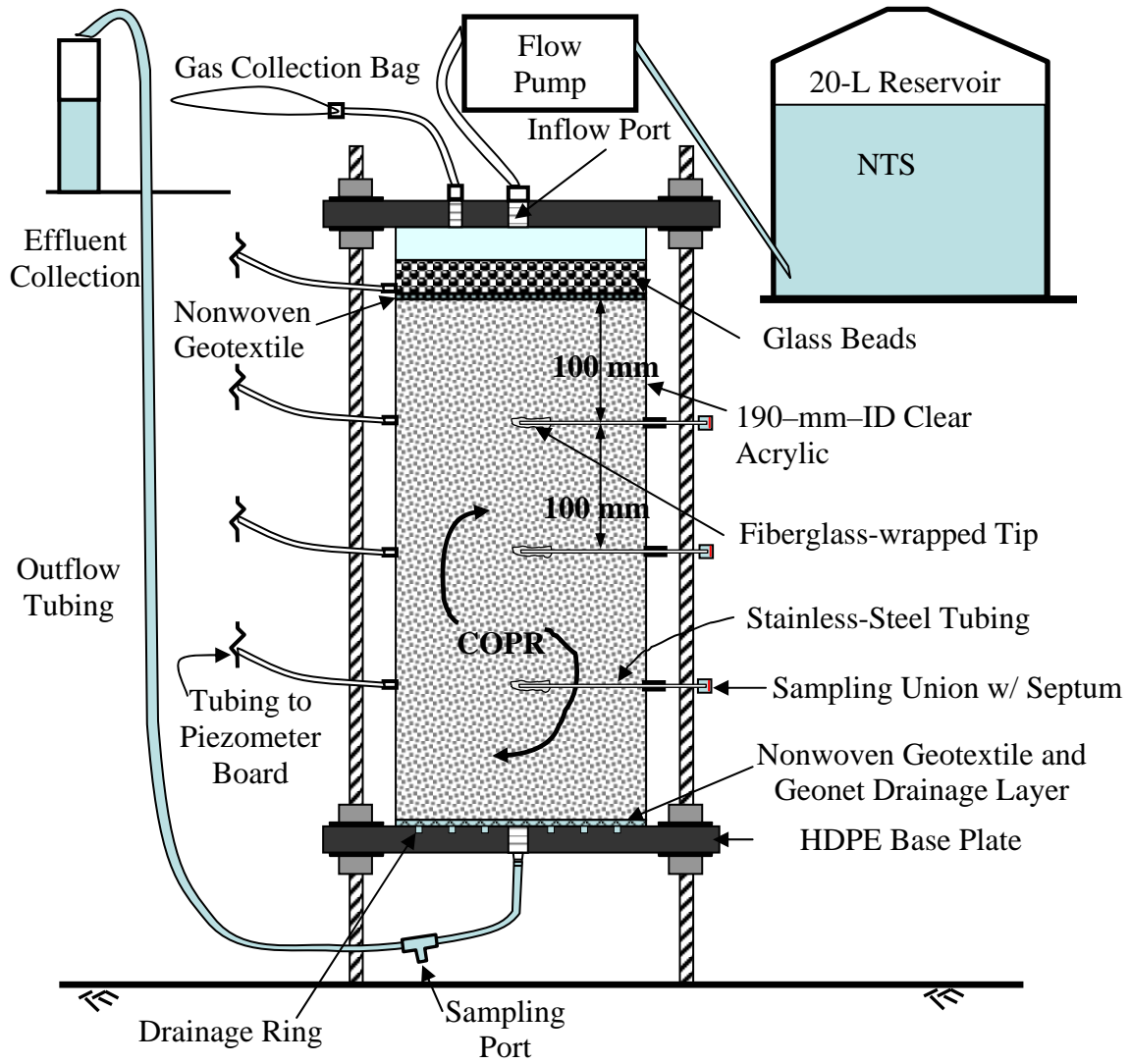


Figure 1. Schematic of Setup for Column Test.

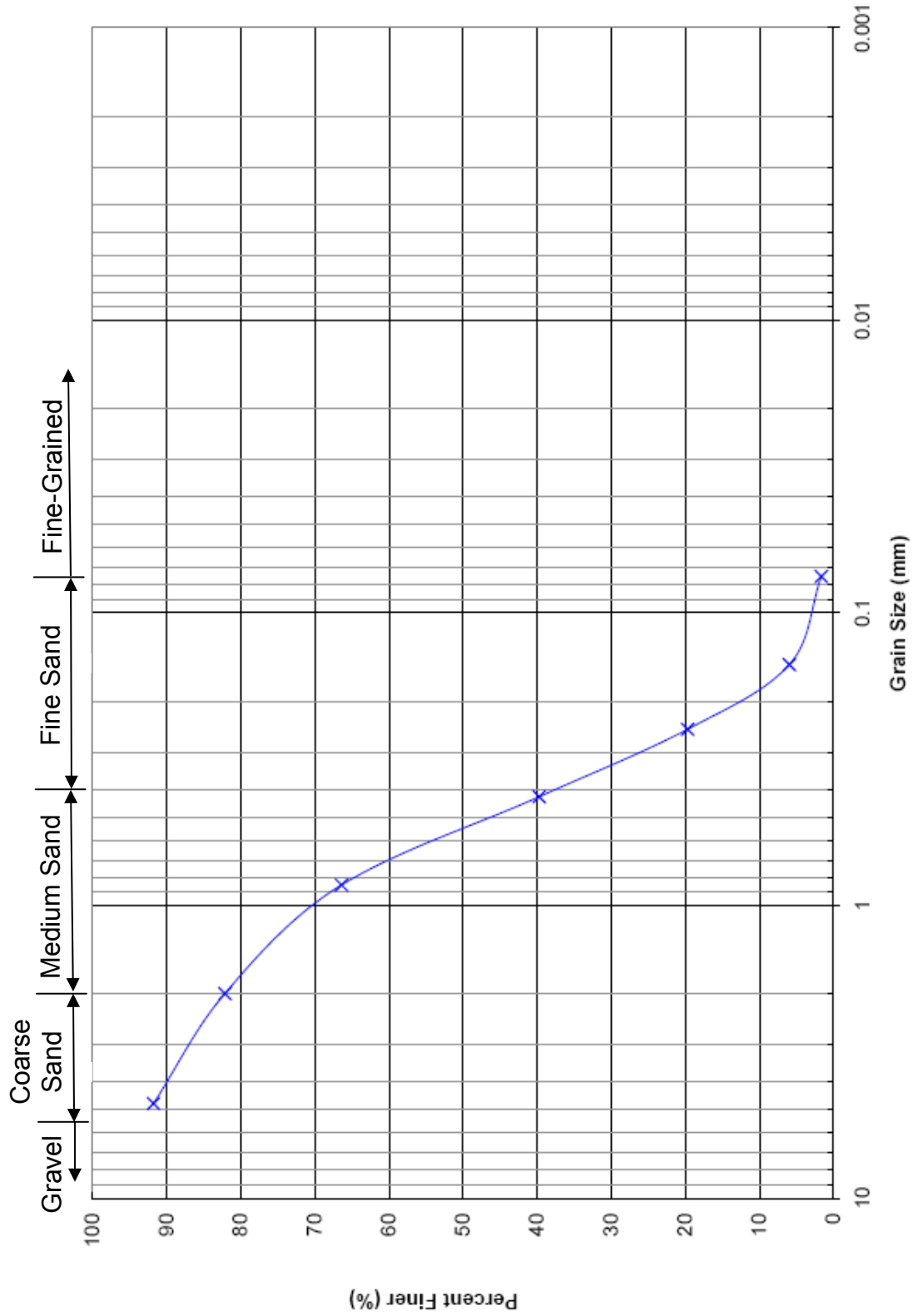


Figure 2. Grain-size Distribution of COPR Used in Column Study.

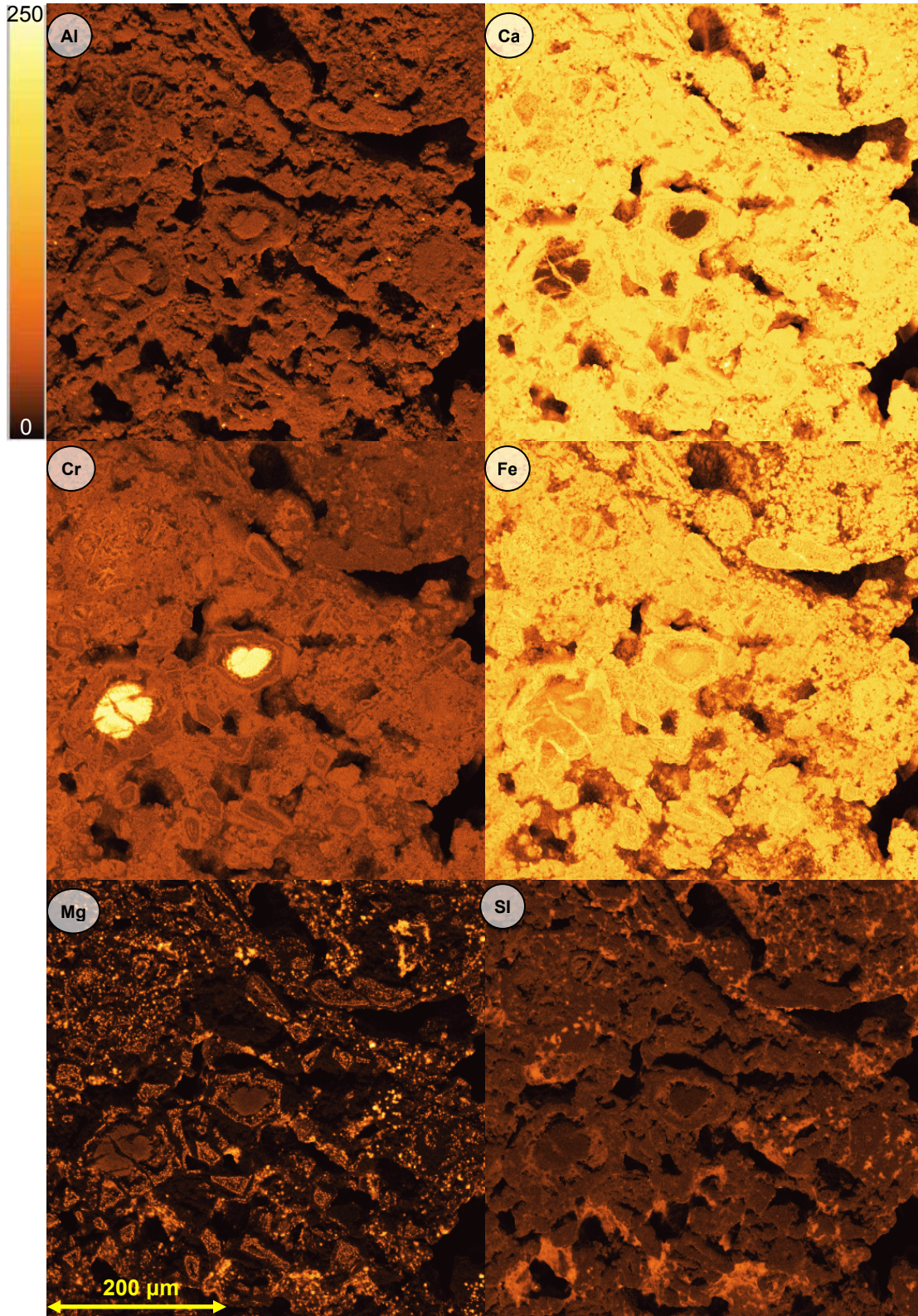


FIGURE 4. X-ray maps for Al, Ca, Cr, Fe, Mg, and Si in untreated COPR. The relative intensity scale is 0 (zero concentration) to 250 (highest concentration).

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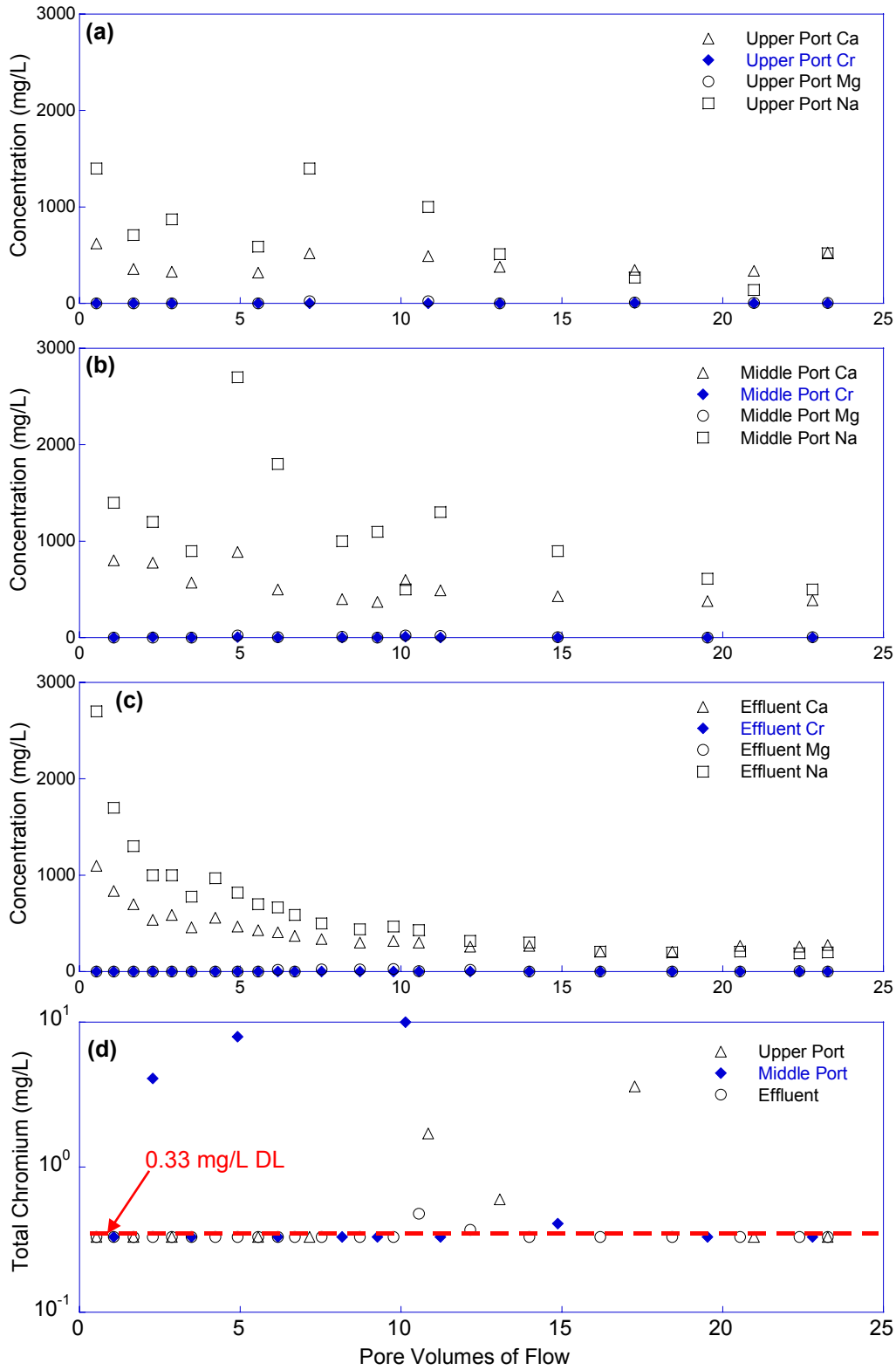


Figure 5. Column Leaching from the (a) Upper, (b) Middle, and (c) Effluent Ports. In (d), the total chromium concentrations are provided on a logarithmic scale.

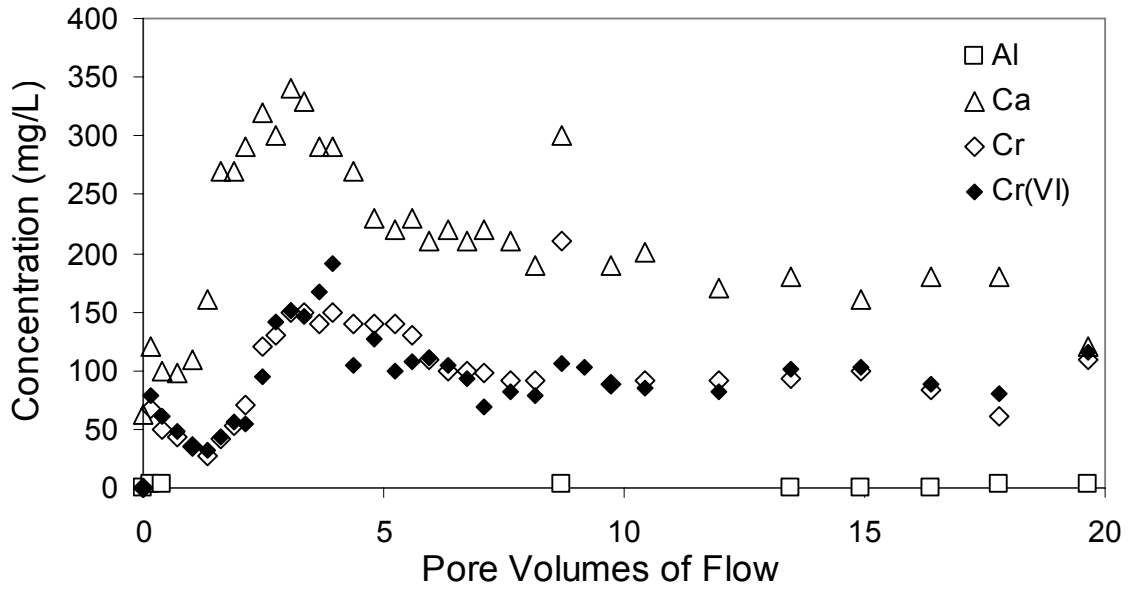


Figure 6. Column Leaching from COPR Permeated with Synthetic Groundwater (from Tinjum et al., 2005).

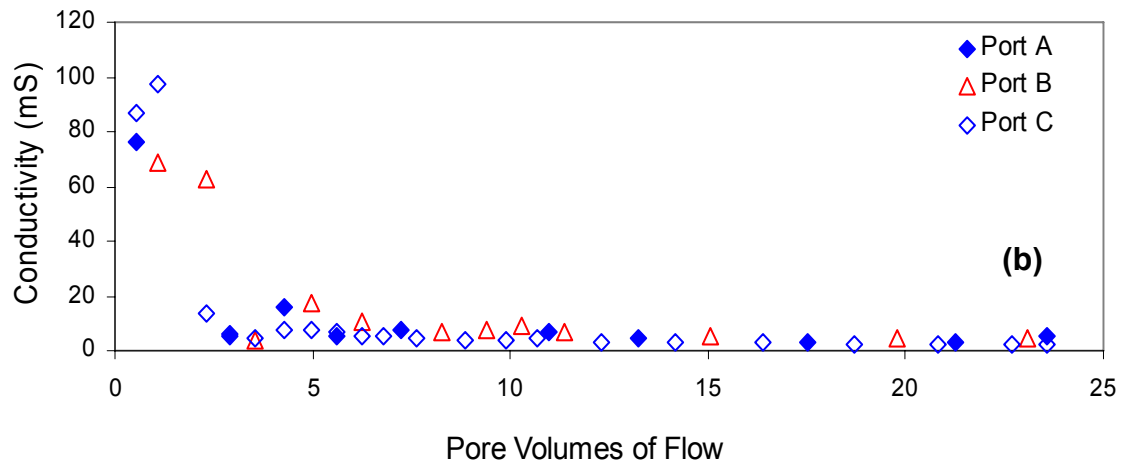
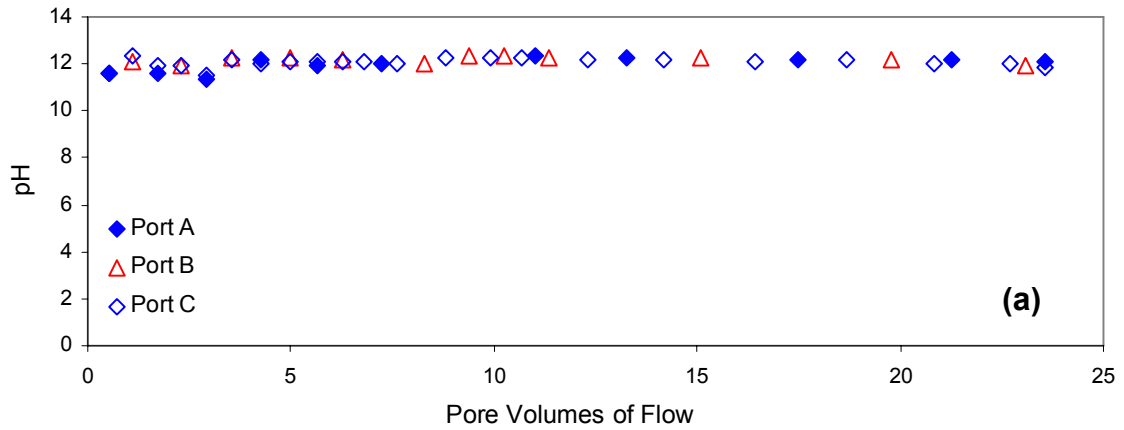


Figure 7. Relationships of (a) pH and (b) Conductivity for the COPREX Column.

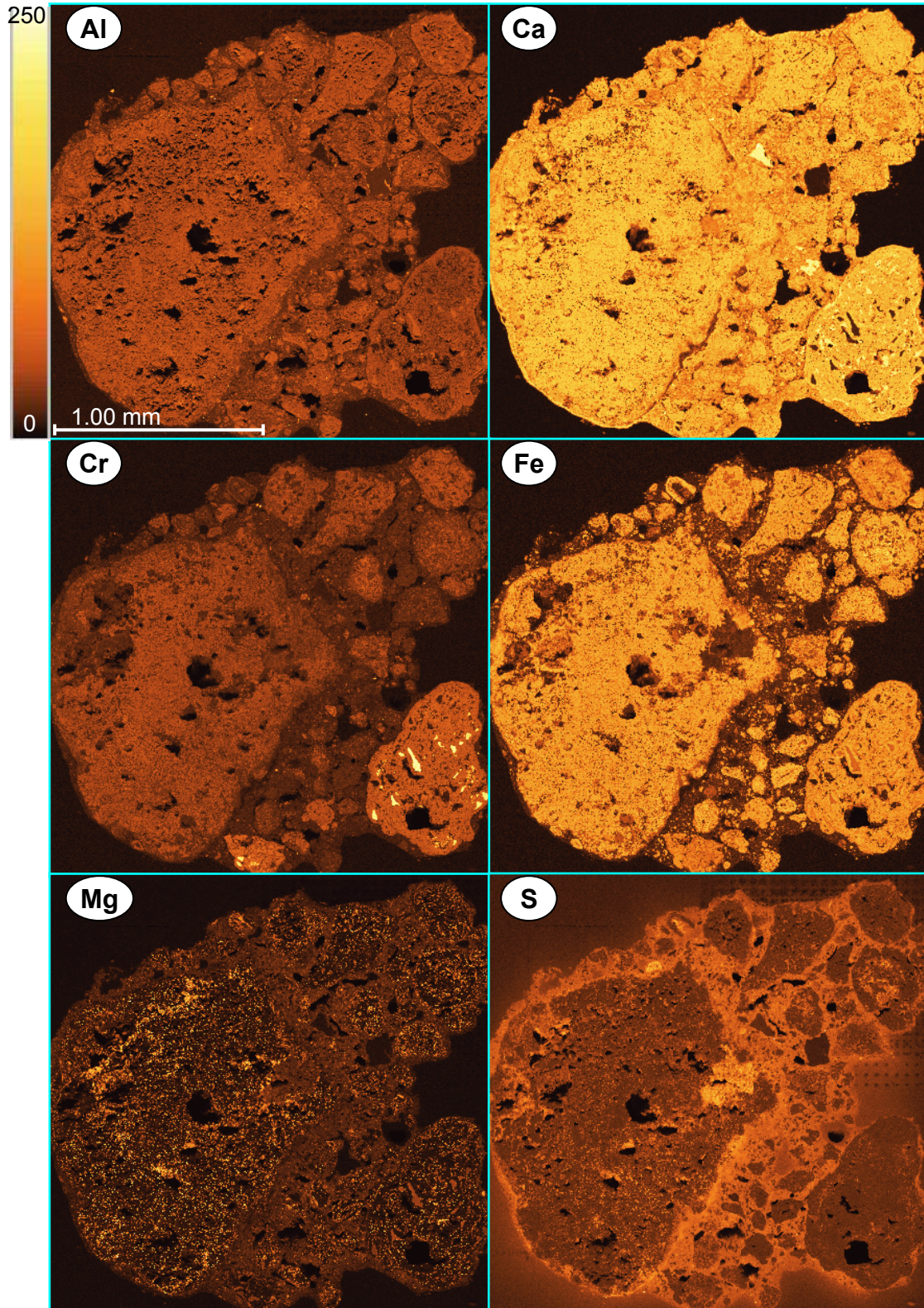


FIGURE 8. X-ray maps for Al, Ca, Cr, Fe, Mg, and S in treated COPR. The relative intensity scale is 0 (zero concentration) to 250 (highest concentration).

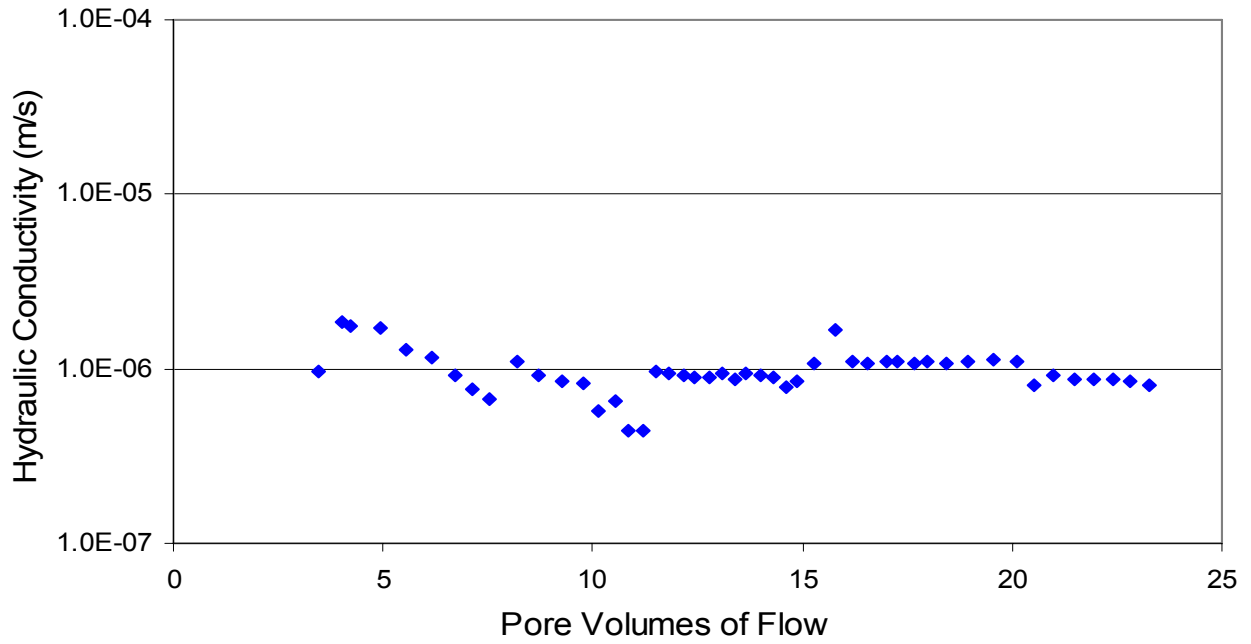


Figure 9. Hydraulic Conductivity Response for the COPREX-treated COPR.