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Assessment of Corrosion Potential of Coarse Backfill Aggregates for Mechanically Stabilized Earth Walls

Anita Thapalia, David M. Borrok, Soheil Nazarian, and Jose Garibay

The service life of mechanically stabilized earth walls depends on the rate of corrosion of the metallic reinforcements used in their construction. The assessment of corrosion potential requires an accurate evaluation of pH, resistivity, and sulfate and chloride concentrations of aqueous solutions in contact with the surrounding aggregate. Highway agencies tend to use larger aggregates that contain only a small amount of fine material (passing the Number 40 sieve) in the backfill. Evaluation of the electrochemical parameters of coarse aggregates is challenging because traditional evaluation methods call for the use of fine material. In this study, the suitability of traditional soil characterization techniques for use with coarse aggregates was assessed through leaching experiments performed on coarse limestone and dolomite aggregates from six quarries in Texas. Chemical differences were isolated from size-related kinetic leaching effects by comparing the results from same-sized material collected in the field with material derived from the crushing of larger (≥⅜ in.) aggregates in the laboratory. The testing demonstrated that the fines collected from the field were enriched in chemicals that, when exposed to water, decreased pH and resistivity and increased sulfate concentrations compared with the bulk rock. This was likely the result of sulfur compounds in the atmosphere reacting with carbonate rocks to produce reactive surface layers that were mechanically abraded into the fines. This phenomenon could bias traditional soil testing results and, therefore, the assessment of corrosion potential. This study demonstrated that a more accurate assessment of the electrochemical parameters can be obtained by crushing the coarse material to meet testing size specifications.

Mechanically stabilized earth (MSE) walls consist of layers of compacted aggregate backfill, usually reinforced by galvanized steel strips or meshes. The service life of MSE walls depends on the corrosion rate of the metallic reinforcements. Accelerated corrosion of the metallic reinforcements can cause the sudden and catastrophic failure of MSE structures (*1*). The corrosion rates of the metallic reinforcements are directly linked to the electrochemical properties of the compacted aggregate. Hence, before construction it is crucial to effectively evaluate the corrosive potential of the aggregate.

Most state Departments of Transportation (DOTs) specify acceptable ranges for the electrochemical characteristics of backfill aggregates as a surrogate for the potential corrosivity of backfill. These parameters and their acceptable ranges—which are generally adapted or modified from those provided by AASHTO or ASTM—include pH, resistivity, chloride (Cl) concentration, sulfate (SO_4) concentration, and total organic content. Many of these methods specify the use of materials that are finer than either the Number 10 (2 mm) or Number 40 (425 μm) sieve. This size limitation poses a significant problem when coarse backfills, like the Texas DOT Type A (50% to 100% retained on the 1/2 in. sieve and 85% to 100% retained on the Number 40 sieve) or Type D (85% to 100% retained on the ⅜ in. sieve), are used for MSE construction. In many cases, these coarse backfills contain only a small percentage of materials finer than the Number 10 sieve. Hence, current tests focus only on a small subset of the aggregates in the backfill, with the assumption that these fines are chemically representative of the bulk rock. This assumption has not been adequately tested, and it remains unclear whether fine grain–based testing methods are adequate for predominantly coarse aggregate backfills. Because the chemical test results directly impact whether an aggregate is accepted or rejected for MSE construction, the financial consequences of improper characterization of aggregates can be serious. The unnecessary rejection of a backfill, as a result of ineffective or biased testing methodologies, could result in significant financial losses. Conversely, erroneous acceptance of a backfill that has a high potential to cause corrosion can reduce the service life of MSE walls and, possibly, result in catastrophic failure. In this investigation, leaching experiments were used to test whether traditional fine-grained testing methodologies are adequate to assess the corrosive potential of coarse aggregates.

METHODOLOGY

Collection, Classification, and Preparation of Backfills

The Texas DOT allows four acceptable gradations (Type A through Type D) for the backfill of MSE walls in its standard specifications for roadway and bridge construction (*2*). The so-called rock backfills (i.e., Types A and D) are being used more frequently and contain more than 85% materials retained on the Number 4 sieve. A survey of 25 Texas DOT districts revealed that 44% of MSE walls used Type A (30%) or Type D (14%) backfill, with the constituents of more than 73% of the backfill materials being limestone. The concern of the Texas DOT is whether traditional electrochemical tests are applicable to these freely drainable coarse backfills. To address this concern, Type A or Type D backfills from six quarries in Texas were collected. All six materials were sampled from stockpiles that are actively used in the construction of MSE walls.

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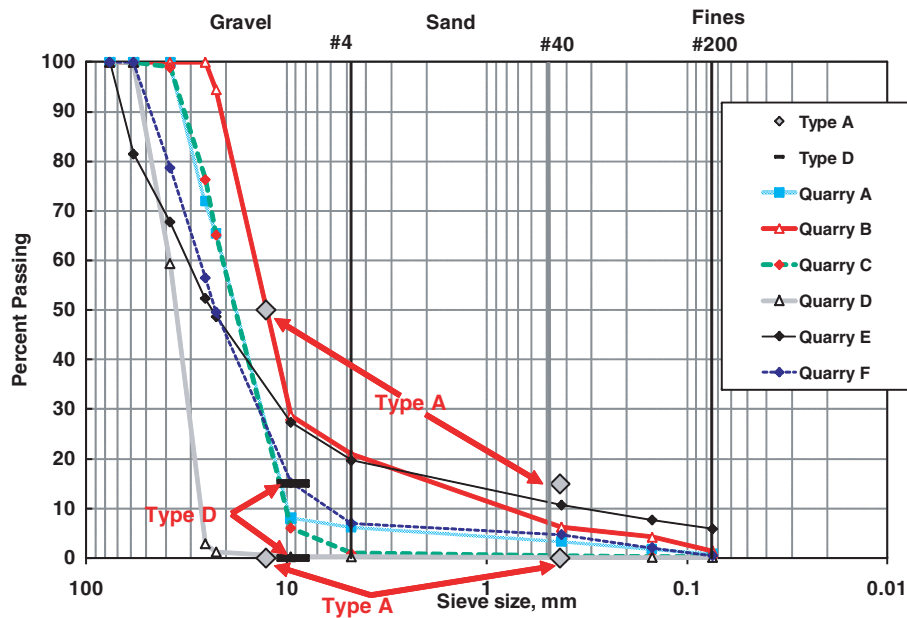
FIGURE 1 Grain size distributions of selected backfills.

Five of the backfills were limestone and one was dolomite. The gradation curves for the six backfills, along with the specification limits for Types A and D, are presented in Figure 1 and summarized in Table 1. The materials from Quarries A, C, D, and F met the Type D gradation specifications, and the materials from Quarries B and E were Type A backfills. The distribution of the backfills was a good representation of the statewide use of the materials. The plasticity index (PI) of each backfill is shown in Table 1. Material from Quarries B, C, and D were determined to be nonplastic, and material from Quarries A, E, and F all had a PI of about four. The Texas DOT specification did not specify a minimum PI, but it did specify a maximum of 30.

Three alternative means of assessing the hardness of the aggregates are also presented in Table 1: the wet ball mill, the aggregate crush-

ing value (British Standard 812), and the aggregate impact value (British Standard 812) tests. The most crush-susceptible materials were from Quarries A, E, and F.

The optimum moisture contents and the maximum dry densities for each material are also shown in Table 1. It was not possible to develop moisture-density curves for the backfill materials from Quarries D, B, and C. These materials would not absorb any water, and the compacted specimens crumbled as soon as they were extracted. Materials from Quarries A, E, and F exhibited the highest crushing potential and yielded reasonable moisture-density curves because the coarse aggregates severely crushed to finer materials during compaction. In practical terms, even though the materials from these quarries were specified and delivered as Type A or Type D backfill, they looked and behaved like a finer backfill material.

TABLE 1 Material Constituents of Backfill Materials

Parameter	Quarry, Rock Source, and Classification					
	A Limestone Type D	B Limestone Type A	C Limestone Type D	D Dolomite Type D	E Limestone Type A	F Limestone Type D
Gradation[a]						
Gravel	94	79	100	99	80	93
Coarse sand	3	15	0	1	9	2
Fine sand	2	5	0	0	5	4
Fines	1	2	0	0	6	0
Atterberg limits						
Liquid limit	16	Nonplastic	Nonplastic	Nonplastic	15	22
Plasticity index	3				4	4
Hardness of aggregates						
Wet ball mill (%)	11	6	1	1	NA	30
Aggregate impact value	19	11	13	9	25	28
Aggregate crushing value	29	22	26	16	37	34
Moisture density properties						
Optimum moisture content (%)	9.0	NA	NA	NA	6.0	8.3
Maximum dry unit weight (pcf)	130	108	95	122	129	123

NOTE: NA = not applicable.
[a]Gravel = retained on Number 4 sieve, coarse sand = retained on Number 40 sieve and passing Number 4 sieve, fine sand = retained on Number 200 sieve and passing Number 40 sieve, fines = passing Number 200 sieve.

TABLE 2   Resistivity, pH, and Chloride and Sulfate Contents of Backfills

Backfill Material	Resistivity Tex-129-E (AASHTO T-288) (Ω-cm)	pH Tex-128-E (AASHTO T-289)	Chloride Tex-620-J (AASHTO T-291) (mg/kg)	Sulfate Tex-620-J (AASHTO T-290) (mg/kg)
A	2,322	7.92	116.8	309.6
B	8,815	8.79	326.0	151.6
C	1,871	7.93	349.8	751.5
D	7,740	8.69	611.3	460.7
E	2,365	8.54	204.7	238.9
F	1,967	8.14	91.5	64.7
Texas DOT limit	$\geq$3,000	5.5–10	$\leq$100	$\leq$200

NOTE: Shaded cells represent failure of Texas DOT criteria for acceptable corrosion potential.

The geochemical characterization of the backfill materials with the standard Texas DOT methodologies is summarized in Table 2. Although the Texas DOT methods can be linked to their AASHTO counterparts (also listed in Table 2), some modifications existed and are discussed in the appropriate sections below. According to the Texas DOT's specifications, most of the materials would not have passed the chloride or sulfate concentration criteria, and the samples from Quarries A, C, E, and F would also have failed the resistivity criterion. The pH for all the samples was within the 5.5 to 10 window of acceptability.

Leaching Tests

To characterize more representative specimens of the backfills, the U.S. Geological Survey's field leach test (USGS FLT) was employed. The FLT is effective at evaluating the geochemical properties of leachate from a variety of soils and rocks, and FLT results are comparable to those obtained using the Environmental Protection Agency's synthetic precipitation leaching procedure (USEPA 1312 SPLP) (3) and the European "shake test," recently standardized by the Comité Européen de Normalisation (EN-12457-3) (4). The advantages of the USGS FLT are that it is rapid, inexpensive, has no aggregate size restrictions, and produces enough leachate for additional analytical tests. The FLT method utilizes a 50-g sample of soil or rock that is added to 1,000 mL of distilled water in a 1-L plastic bottle. The solution is shaken vigorously for 5 min, and, after settling for 30 min, the pH and resistivity of the fluid are measured in situ, and filtered (0.45 μm) samples are collected for laboratory analysis (3). In this study, the FLT method was slightly modified: the mass of the rock was increased to 100 g, and the tests were continued for days or weeks with intermittent sampling. The increase in sample mass from 50 g to 100 g was necessary to accommodate the largest pieces of rock. This solid-to-liquid ratio (100 g to 1 L) is identical to that used in the European "shake test" (EN-12457-3) and the Texas DOT Tex-620-J method; these measure Cl and SO_4 concentrations, respectively. An ExTech EC 500 instrument was used to measure the pH and the resistivity of the FLT samples, and Cl and SO_4 analyses were performed using a Metrohm ion chromatograph. To evaluate the impact of the aggregate size on the results, the sieved backfill materials were divided into six bins, as shown in Table 3.

To obtain most geochemical results under current specifications, an exorbitant amount of backfill has to be sieved to gain adequate quantities of the required size materials. In most applications, this process is impractical. To evaluate a more practical approach, the aggregates from each quarry that were retained on the ⅜-in. sieve were crushed in the laboratory with a Massco crusher and sieved to obtain adequate materials for six bins of the same sizes as those used for the field samples. These samples were referred to as "laboratory-crushed samples," and the samples collected and sieved directly from the quarries were referred to as "field samples." Because the laboratory-crushed samples were obtained from the mechanical crushing of large pieces of rock, they were considered more homogeneous in composition and more representative of the true chemistry of the aggregate. The field samples were subject to natural weathering and degradation processes, and the different size fractions may not have been chemically homogeneous. The purpose of preparing two sample sets of the same sized materials, one collected from the field and the other collected from the crushing of larger rock, was to isolate the chemical differences through the elimination of size-related kinetic leaching effects. Chemicals typically leach into a solution more rapidly from smaller-sized aggregates because the surface-to-volume ratios increase with decreasing aggregate size.

RESULTS AND DISCUSSION

pH Measurements

Figure 2 presents the pH measurements, obtained using the FLT method, from different size fractions of the field and laboratory-crushed samples. The pH of the leachate ranged from 8.5 to 10.1, which is typical of carbonate rock; however, there was significant variation in pH among different sized materials and between laboratory-crushed and field samples. The size-dependent variation in pH was probably attributable to kinetic leaching effects, whereas the differences between the laboratory-crushed and field samples, when compared at the same sieve size, were primarily attributable to chemical

TABLE 3   Bin Sizes for Sieved Materials

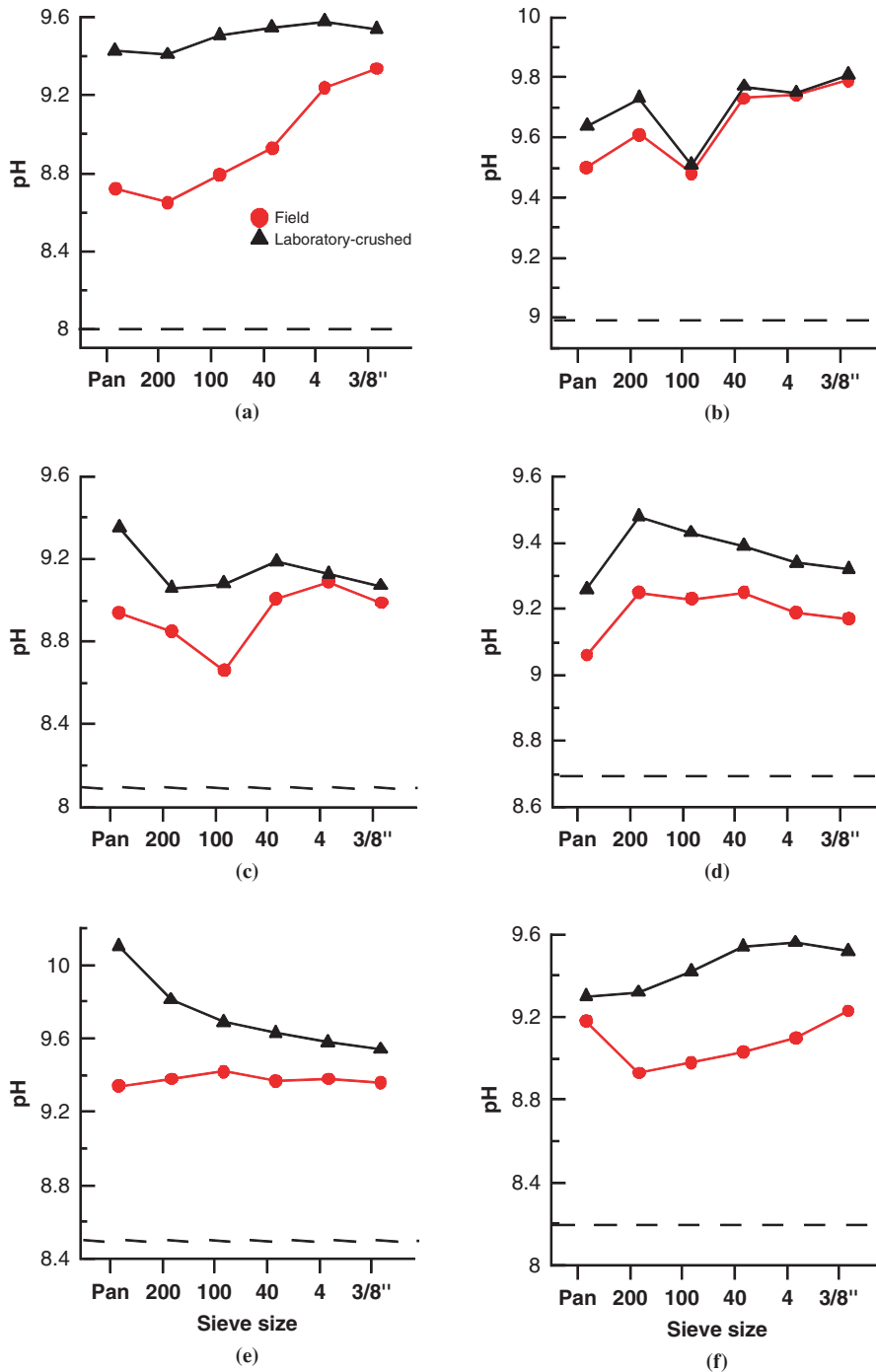| Bin Designation	Passing Sieve	Retained on Sieve
Pan	No. 200	NA
200	No. 100	No. 200
100	No. 40	No. 100
40	No. 4	No. 40
4	⅜ in.	No. 4
⅜ in.	NA	⅜ in.

FIGURE 2 In situ pH measurements from FLT tests (similar to AASHTO T-289) completed using different sizes of field and laboratory-crushed aggregate from Quarries A–F (dashed line = results from Tex-129-E): (a) Quarry A, (b) Quarry B, (c) Quarry C, (d) Quarry D, (e) Quarry E, and (f) Quarry F.

differences. The aggregates sieved from the field samples exhibited a lower pH than the laboratory-crushed aggregates, by as much as 0.8 log units, and the magnitude of this difference was generally greatest for the smallest size fractions (finer than the Number 40 sieve).

Figure 3 presents the pH measurements for different size fractions of Quarry A material as a function of leaching time during the FLT

experiments. Again, the pH of the samples sieved in the field was lower than the pH of the laboratory-crushed samples of the same size. The magnitude of the pH difference was greatest for the smaller-size fractions and became insignificant for the larger-size fractions (Number 4 and ⅜ in.). Although in a carbonate rock system pH generally decreases toward an equilibrium value of around 8.3 over time, the magnitude of the pH difference between the field and laboratory-crushed samples
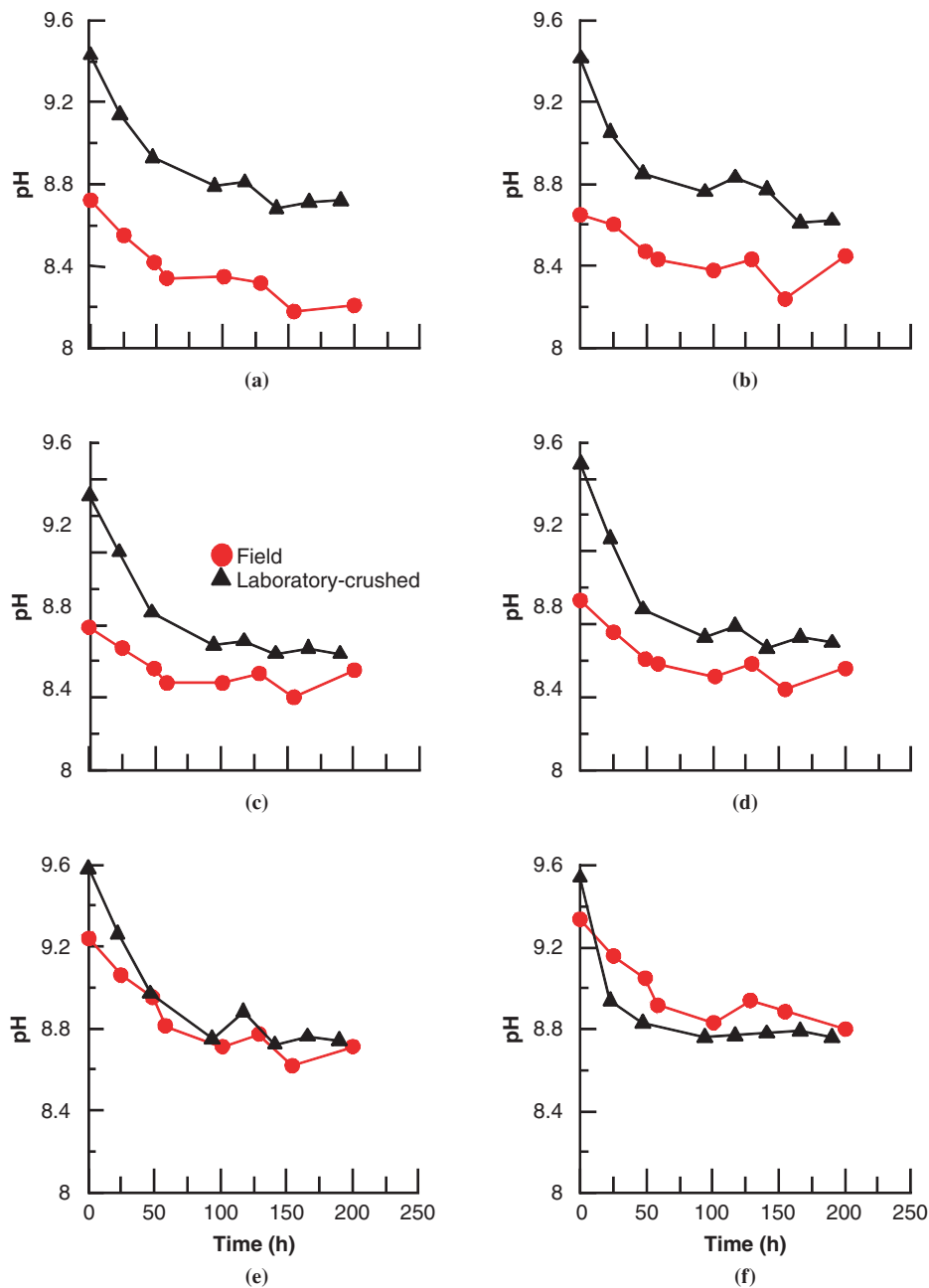
FIGURE 3   pH of field and laboratory-crushed aggregate from Quarry A, collected during FLT experiments, as a function of leaching time: (*a*) pan, (*b*) Bin 200, (*c*) Bin 100, (*d*) Bin 40, (*e*) Bin 4, and (*f*) Bin ⅜ in.

persisted over the more than 200-h duration of the experiments (Figure 3). This further supports the interpretation that the laboratory-crushed and field samples were chemically different, particularly for the finer than Number 40 sieve fractions.

The pH of each quarry material was additionally evaluated by the Tex-128-E method, which calls for the leaching of the soil at 45°C to 60°C. This is a modification from the corresponding AASHTO T-289 and ASTM G-51 methods (and the FLT method employed in this study) in which the pH is determined from the leaching of the soil at room temperature. The Tex-128-E results, shown as dashed lines in Figure 2, ranged from a pH of about 8 to 9 and produced consistently

lower pH values than those from the FLT method. The reason for this discrepancy was that the higher temperature employed in the Texas DOT method accelerated leaching, moving the system toward equilibrium more rapidly. The FLT pH measurements began to converge with the Texas DOT values when the leaching time was increased to 48 h. However, a possible pitfall of the Texas DOT method is that the activity of hydrogen (and thus pH) changes with temperature. The pH measured at 60°C is about 0.4 log units less than the pH measured at 25°C. As such, a correction of the pH measured at higher temperatures is required to avoid an underestimation of the pH of likely field conditions.

Resistivity

Figure 4 presents the resistivity values recorded in the FLT solutions from the six bins for each of the backfill materials. Resistivity is a reflection of the total ion concentration of the solution, and more resistive samples correspond to lower ion concentrations. The variations in resistivity among the laboratory-crushed size fractions for aggregates from an individual quarry were reflective of the differences in leaching rates attributable to size. The smallest laboratory-crushed fractions were less resistive than the larger laboratory-crushed fractions because more ions had leached into the solution by the time the samples were measured. With only one exception (Quarry B), the finer than Bin 40 field samples were less resistive than the corresponding laboratory-crushed samples. Hence, the finer than Bin 40 field fractions were characterized by a greater quantity of rapidly leachable material than the corresponding laboratory-crushed fractions. The resistivity values measured by the FLT method are not comparable to those measured by traditional soil-box methods (e.g., AASHTO T-288; ASTM G-187; and Tex-129-E), because the liquid-to-volume ratios and the spacing and geometries of the electrodes are method-specific parameters.
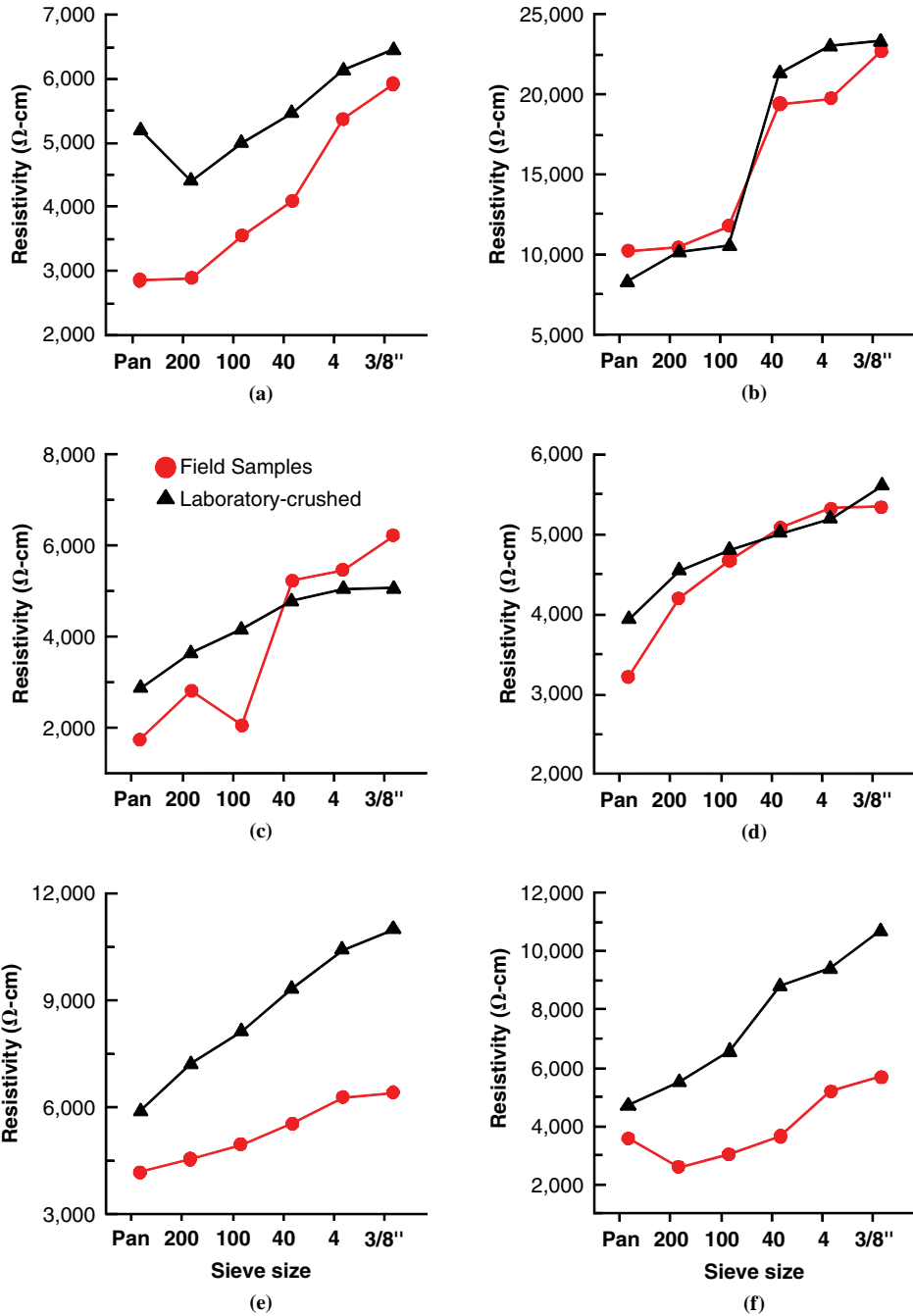

FIGURE 4   Resistivity measured during FLT experiments on different sized field and laboratory-crushed aggregates from Quarries A–F: (*a*) Quarry A, (*b*) Quarry B, (*c*) Quarry C, (*d*) Quarry D, (*e*) Quarry E, and (*f*) Quarry F.

Sulfate and Chloride Content

Figures 5 and 6 represent the results of the SO_4 and Cl analyses of the FLT leachates from different bins. The SO_4 concentrations of the fine field samples were always greater than those for the corresponding laboratory-crushed samples. In some cases, leachate from the field samples contained more than three times as much SO_4 as the laboratory-crushed samples. The SO_4 concentrations of the larger-size fractions (coarser than Bin 40) of the field material more closely matched those of the laboratory-crushed material (Figure 5). This demonstrates that SO_4 was enriched in the finer field samples compared with SO_4 in the bulk rock. In general, the Cl contents of the field and laboratory-crushed samples were similar, with the exceptions of Quarries E and F (Figure 6). This demonstrates that, in limited cases, Cl was enriched in the finer field samples compared with the bulk rock. Many of the finer field samples were additionally enriched in nitrate compared with the bulk rock (data not shown).
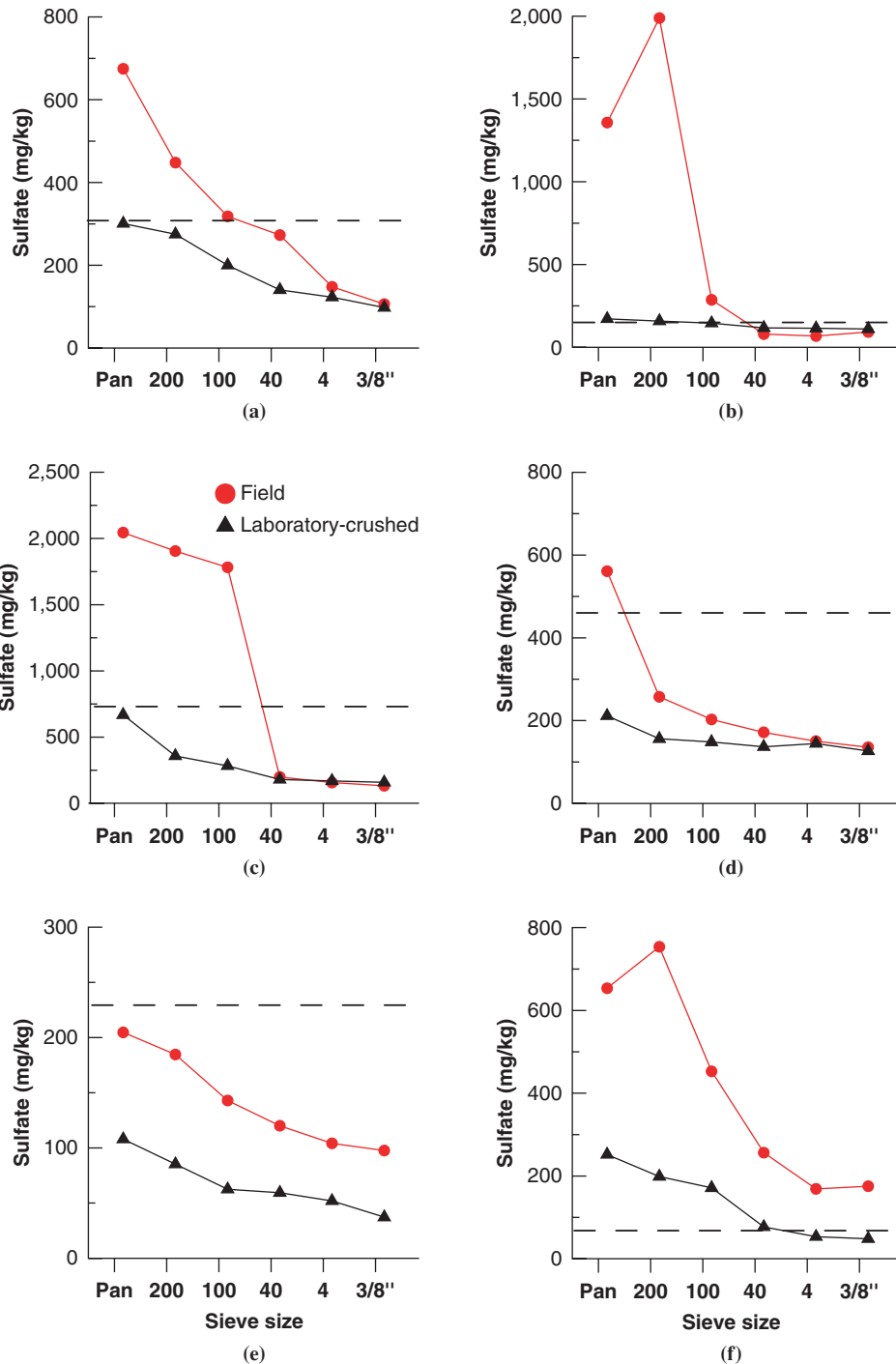

FIGURE 5 SO_4 concentrations of FLT (similar to AASHTO T-290) leachate for field and laboratory-crushed aggregate from Quarries A–F (dashed line = results from Tex-620-J): (a) Quarry A, (b) Quarry B, (c) Quarry C, (d) Quarry D, (e) Quarry E, and (f) Quarry F.
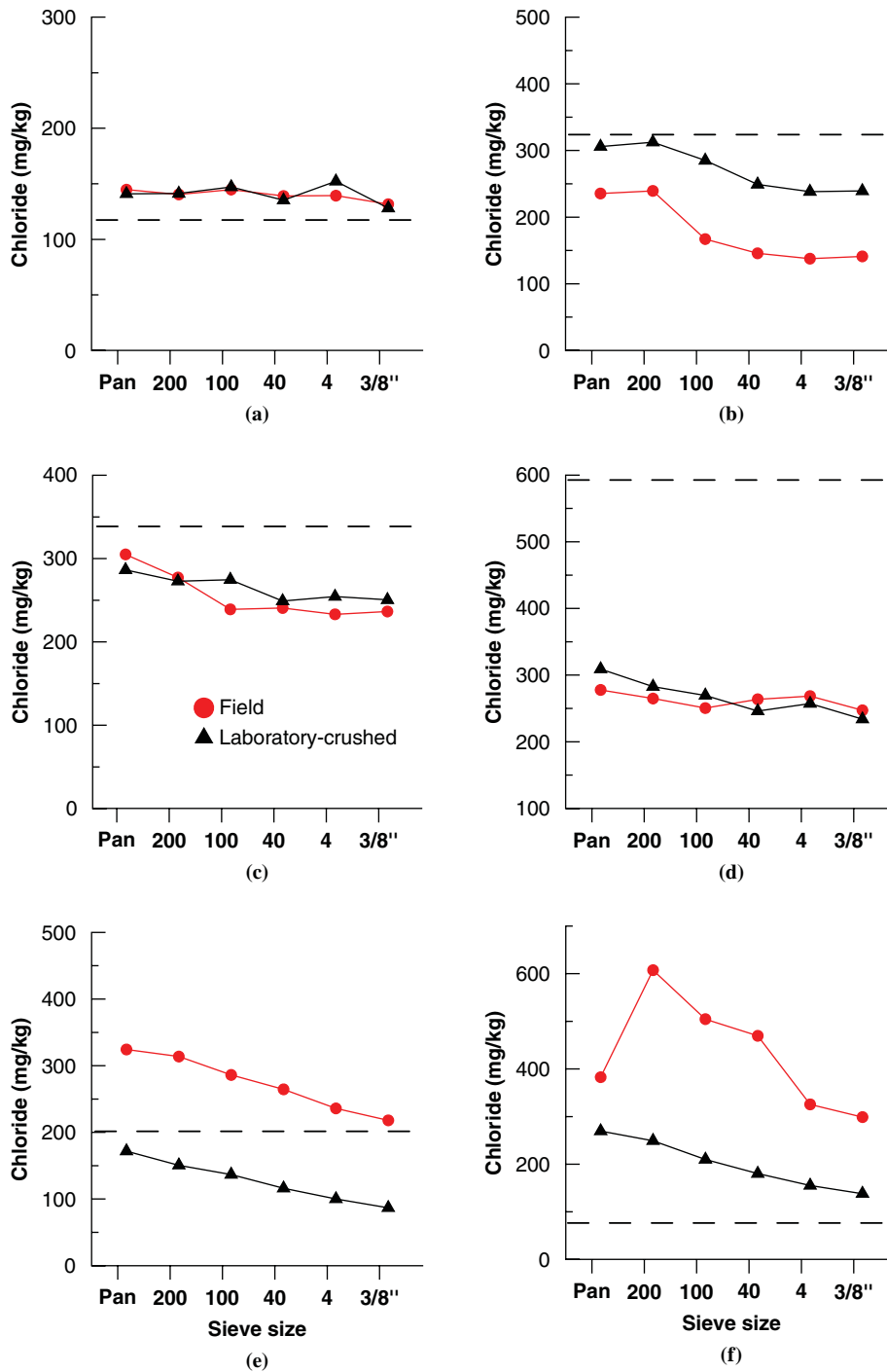
FIGURE 6   Chloride concentrations of FLT (similar to AASHTO T-291) leachate for field and laboratory-crushed aggregate from Quarries A–F (dashed line = results from Tex-620-J): (a) Quarry A, (b) Quarry B, (c) Quarry C, (d) Quarry D, (e) Quarry E, and (f) Quarry F.

For Quarries A, B, and C, there was virtually no difference among SO_4 concentrations for the finest size fractions measured by the FLT method (laboratory-crushed samples) when compared with the Tex-620-J method (dashed line in Figure 5). Unlike the Texas DOT pH and resistivity testing methods, the Tex-620-J method utilizes laboratory-crushed material. This is also a deviation from the root AASHTO T-290 and ASTM C-1580 methods for evaluating the

SO_4 content of soils; those two methods utilize materials collected from the field. Sulfate concentrations measured with the Tex-620-J method were much greater than FLT values for Quarries D and E. This discrepancy was likely attributable to the fact that the Tex-620-J method involves aggressive leaching at elevated temperatures (40°C to 60°C), whereas the FLT, AASHTO, and ASTM methods are performed at room temperature. Higher temperatures

typically result in anomalously high concentrations of chloride and sulfate compared with other testing methods. Similar results were observed for chloride concentrations: the values obtained using the Tex-620-J method were either similar to or greater than those obtained by the FLT method for all quarries except Quarry F. For Quarry F, both SO_4 and Cl concentrations measured by the Tex-620-J method were less than those measured by the FLT method, suggesting that the higher testing temperature induced some chemical or physical changes that were not observed at room temperature.

PROCESSES LEADING TO CHEMICAL DIFFERENCES BETWEEN FINE AND COARSE AGGREGATES

The pH, resistivity, and chemical data demonstrated that the fine (passing the Number 4 sieve) aggregates collected at the quarry sites were not electrochemically representative of the bulk rocks. The fines were enriched in easily leachable chemical species that, when exposed to water, decreased pH, decreased resistivity, and increased SO_4 concentrations compared with the bulk rock. This enrichment was most likely the result of a chemical weathering phenomenon related to atmospheric acid deposition (5–7). Sulfur and nitrogen oxide compounds in the atmosphere react with carbonate rocks to produce reactive surface layers (typically of soluble sulfate minerals and dry acids) that are easily mechanically abraded and easily chemically leached (8, 9). Emissions from the heavy equipment typically used in quarries (loaders, dozers, trucks, etc.) can substantially add to sulfur and nitrogen oxide emissions, thereby compounding the problem. The reactive surface layers are likely ground off and mechanically abraded during transport and movement of the coarse aggregate thereby biasing the chemistry of the fines. This chemical weathering process is probably limited to carbonate-rich rocks because of their surface reactivity (10). An alternate, but less likely, explanation is that excess sulfate is attributable to the oxidative weathering and physical breakdown of sulfide minerals like pyrite in these rocks. However, in this case, none of the carbonate aggregates contained visible sulfide minerals, and no such materials were detected through x-ray diffraction.

IMPLICATIONS FOR THE ASSESSMENT OF CORROSIVE POTENTIAL WITH TRADITIONAL SOIL TESTING METHODS

This study demonstrated that for coarse, carbonate-rich aggregates (like the Texas DOT Type A and Type D materials investigated), the fines that develop in the field often comprise only a few percent of the total rock mass (Figure 1) and can be chemically different from the bulk rock (Figures 2–6). This fact can bias traditional AASHTO, ASTM, and Texas DOT soil testing methodologies that call for the use of material collected directly from the field and specify the use of fines. For example, the Texas DOT methods for the assessment of pH, resistivity, SO_4, and Cl call for the testing of material passing the Number 40 sieve, while the AASHTO methods for the same parameters call for the testing of material that passes the Number 10 sieve. Presumably, this testing bias would begin to disappear as aggregate sizes decreased and fines passing these sieve sizes began to comprise more of the total rock mass.

As an illustration of the importance of this testing bias, Figure 7 presents the results of the resistivity testing of the field and laboratory-
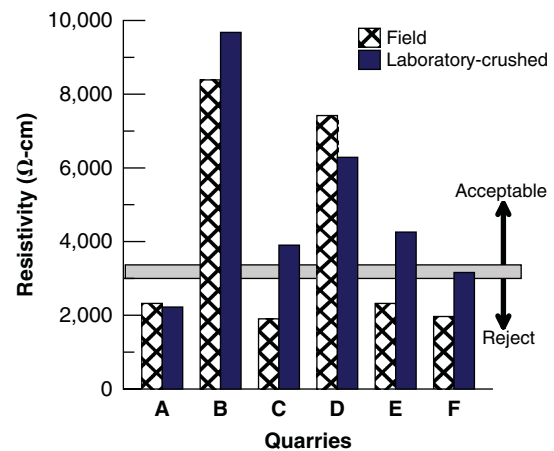

FIGURE 7 Resistivity measurements for laboratory-crushed and field material from Quarries A–F obtained with method Tex-129-E (AASHTO T-288).

crushed material from the six selected quarries; the testing was conducted with the Tex-129-E method (similar to AASHTO T-288, a traditional soil-box resistivity testing method used by many state DOTs). The material tested with this method must have a resistivity greater than 3,000 Ω-cm to be used in the construction of MSE walls in Texas. Going by this criterion, the laboratory-crushed material from five of the six quarries would be acceptable (i.e., >3,000 Ω-cm), but material from Quarries C, E, and F would be rejected based on the resistivity of the field fines (the use of which is specified by the method). In cases like these, in which field fines represent less than 5% of the bulk rock material by mass, it is recommended that only laboratory-crushed materials be used for the assessment of corrosive potential. In these specific cases, the true electrochemical properties of the bulk rock would be better reflected by the laboratory-crushed material than by the field fines. This suggestion is based on the assumption that long-term corrosion rates for metallic reinforcements in MSE walls are best correlated with the average chemical properties of the bulk rock and not with the heterogeneous field fines. Additional work with bench-scale percolation tests of Type A and Type D material that was cyclically saturated with water (2 days) and dried (5 days) demonstrated that any chemical impact of the fines is ephemeral. After just a few cycles, the pore water chemistry was similar to the chemistry obtained from the laboratory-crushed chemical testing. Further work will focus on correlating the corrosion rates of metallic coupons (embedded within the packed aggregates used for the percolation tests) with the electrochemical properties discussed here.

The use of laboratory-crushed material in cases where fines represent less than 5% of the bulk rock may require changes to several of the current AASHTO, ASTM, and Texas DOT methodologies that specify the use of field fines. These standard methods were developed and calibrated to assess the corrosion potential of soils and fine-grained materials. The problems posed by the use of coarse rock fragments for MSE construction were not considered. Hence, modification of the existing methods for these special cases may be appropriate. Moreover, in many cases, simplistic leaching tests that use representative sample sizes, like the FLT, may be equally (or more) effective, compared with traditional AASHTO, ASTM, or Texas DOT methods, for the assessment of the Cl and SO_4 concentrations of coarse aggregates. However, as recently pointed out by

Thornley et al. in an investigation of the rapid corrosion of metallic reinforcements within a set of MSE walls in Nevada, bulk leaching methods are not comparable with traditional soil-box testing for the evaluation of resistivity (*11*). The soil-box methodologies employ specific electrode geometries for the direct measurement of resistivity in saturated aggregate. Bulk leaching methods oversaturate the aggregate because they use higher liquid-to-volume ratios. This can lead to artificial increases in the measured resistivity of the liquid for batch leaching tests.

ACKNOWLEDGMENTS

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