Comparison of Dynamic Properties between Treated and Untreated Bauxite Residue

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ABSTRACT

Dynamic characteristics of treated and untreated Bauxite Residue (Red Mud) are studied and compared using a cyclic simple shear device. Red Mud (RM) is the by-product waste from the Bayer process during aluminum production that has shown the potential of being reused as fill material in embankment construction, which can reduce the energy consumption of disposing of the mining waste and producing fill materials. There are limited studies on the dynamic characteristics of RM; furthermore, the bauxite slurry's high alkalinity (pH > 12) is a challenge for reusing the material. Past studies have shown two effective and economic neutralization methods: (1) mixing with saline and (2) adding gypsum. This study utilizes a cyclic simple shear device to characterize the dynamic properties of the treated and untreated Red Mud. The experimental results are used to develop the liquefaction capacity curves for the three types of Bauxite Residue: untreated, treated with saline solution, and treated with gypsum, and the results show different liquefaction resistances after pH treatments. Untreated RM specimens show the highest liquefaction resistance, and saline-treated demonstrated the least liquefaction resistance.

INTRODUCTION

Bauxite Residue, known as Red Mud (RM), is a slurry waste from alumina production and has a very high pH value (>12) that results from the Bayer Process, which uses a high quantity of oxides. One hundred twenty million tons of RM are generated each year. The alkaline materials create significant environmental concerns when they are disposed into clay-lined impoundments, levees, or dry stacking (IAI 2019). It is essential to reduce the pH values of bauxite residues before they can be environmental-friendly deposed, or even recycled. Reusing RM can effectively promote sustainability because wastes are turned into civil engineering materials for buildings and backfills (Klauber et al. 2011). Tremendous costs could be reduced by minimizing the expense of waste disposal. Many research projects attempted to study the effects of pH reduction by mixing RM with various solutions such as acids, seawater, gypsum, and carbon dioxide (Gore 2015). Currently, a variety of treatments exist to neutralize RM. This study uses saline and gypsum solutions for RM neutralization.

A common practice from coastal companies is to precipitate carbonates and hydroxides in RM using seawater, reducing the material's pH before transporting and storing (Johnston et al.

2010). In near-shore locations, this method is an economical neutralization alternative (Gore 2015). In a previous study by Menzies et al. (2004), different ratios, by volume, of saltwater to RM (e.g., 1:2, 1:10, 1:20, and 1:50) helped prepare RM as a soil improver for agriculture. The study achieved a pH ranging from 8 to 8.5 and the addition of plant nutrients like Calcium and Magnesium after irrigating the RM using salt water for several weeks. In his study, Menzies (2004) concluded that a ratio of 20 liters of seawater per gram of RM is the most efficient for pH reduction after comparing different neutralization techniques. Another potential treatment agent for RM is gypsum. Gypsum is a mineral frequently used as a fertilizer. Glenister and Thornber (1985) investigated the efficiency of gypsum waste from the fertilizer industry to decrease RM alkalinity, achieving RM neutralization using 50 to 60 g of gypsum per kg of RM. Courtney and Kirwan (2012) also utilized gypsum as a treatment method for RM and successfully reduced the pH of RM from 12.5 to 8. Recently, Machado et al. (2020) determined that, with a reduction rate twice that of the saline method, gypsum is more efficient in reducing the pH of RM.

Multiple studies have investigated the geotechnical properties (e.g., soil classification, hydraulic conductivity, and compressive strength) of Red Mud in the past few decades, indicating RM behaves like inorganic silt or silty clay with low plasticity (e.g., Newson et al. 2006; Nikraz et al. 2007; Xenidis and Boufounos 2008). Investigations conducted by Machado et al. (2020), using a Steady-State Centrifugation (SSC) Unsaturated Flow Apparatus (UFA), demonstrated untreated samples to have a lower unsaturated hydraulic conductivity than saltwater-treated RM samples at the same saturation level. Similarly, gypsum-treated RM samples were determined to have a higher unsaturated hydraulic conductivity than the saline ones. Further results from Machado et al. (2020) from the matric potential determination for both treated and untreated RM samples show, in general, water retention like that of clayey materials, low permeability, and high suction, with a water content range similar to silty soils. All these previous investigations contribute to the goal of reusing RM in civil engineering applications. However, a gap in the understanding of the mechanical properties of RM exists in the current literature.

To the best of the author's knowledge, the effects of RM neutralization on the dynamic properties of clean RM have not been considered in literature at the time of writing. The dynamic properties of treated red mud are vital for utilizing the materials as a backfill material for levee construction in seismic active regions. For this reason, this study aims to characterize the dynamic properties of the treated and untreated RM using a cyclic simple shear device. Some past investigations have studied the strength of untreated RM (e.g., Gore, 2015). Limited studies have compared the mechanical properties of treated and untreated RM (Nikraz et al., 2007). Chen et al. (2021) and Parik and Patra (2020) investigated the use of RM as an additive and its impacts on the dynamic properties of soil mixtures. Nikraz et al. (2007) compared the untreated RM with carbonated mud and bittern mud and concluded that carbonated mud gained strength faster during the summer months, and untreated mud had the highest density during the winter months. Chen et al. (2021) used RM and cement additives to improve the mechanical behavior of loess. Through a cyclic triaxial testing program, Chen et al. (2021) showed that RM-treated loess's dynamic strength and elastic modulus are higher than those of untreated loess. Parik and Patra (2020) performed strain-control cyclic triaxial tests on virgin clay mixed with RM and concluded that the clay-RM mixtures have a 20 to 55% strength increase than the clay-only samples.

TESTING PROGRAM

The cyclic simple shear tests were performed on a Confined Multi-Directional Dynamic Simple Shear (CMDSS) device at Cal State LA (Figure 1). In this study, the apparatus's unconfined and uni-cyclic (i.e., constant volume) capability was used to study the dynamic properties of red mud. The CMDSS device comprises a six-axis load cell that measures and controls the normal and shear loads experienced by soil specimens during testing, with a 10kN and 5kN capacity, respectively, with a $\pm 0.1\%$ accuracy. The placement of the load cell was as close as possible to the specimen's top cap to minimize the effects of machine deflection and alignment frictions in the test results. Three independent electronic actuators allow vertical (Z–axis) and horizontal displacements (X & Y axes). The Z-axis actuator was commanded to maintain the sample height to achieve the cyclic constant volume conditions. Linear Variable Differential Transformers (LVDT) in the X, Y, and Z axes with capacities of 9 mm, 9 mm, and 5 mm, respectively, aided in measuring and controlling the displacement during the testing with a 0.1μm resolution. A critical component is the local LVDT at the vertical alignment, allowing accurate measurements of the vertical deformations of the specimen during consolidation stages and better height control during the shearing phase (Dyvik and Suzuki 2019).

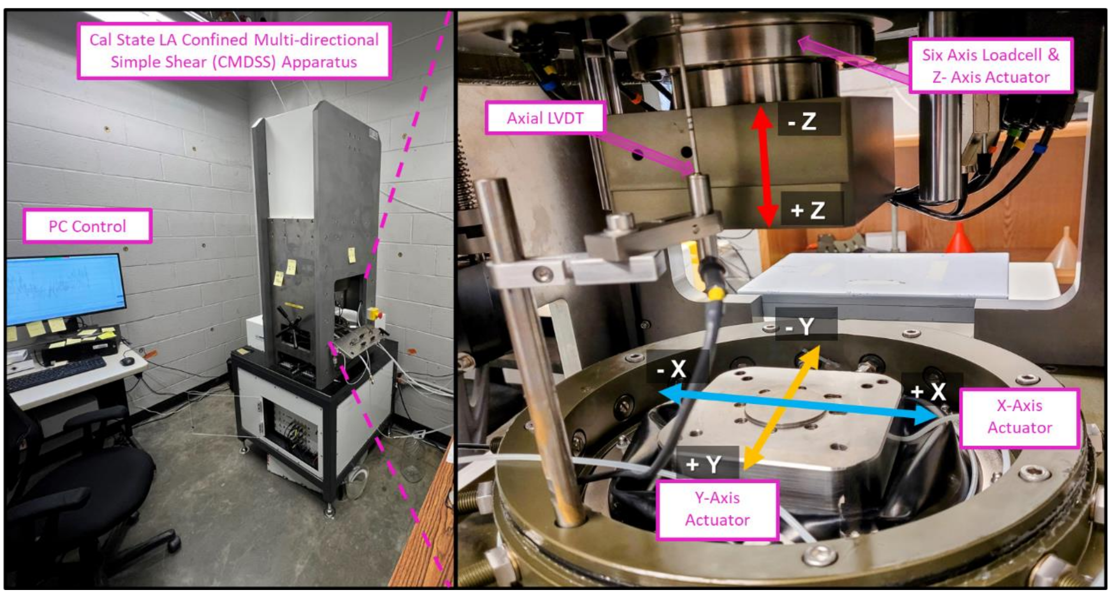

Figure 1. Cal State LA Confined Multi-Directional Dynamic Simple Shear Device

Test Material and pH Neutralization

The RM for this study was obtained from Golder Associates Inc. from a bauxite ore refining facility on the Eastern side of India. The RM in this study was previously used to study the advanced hydraulic properties (Machado et al., 2020). Bulk samples were collected from one of the RM ponds located at the refining facility, and due to confidentiality within the refinery's restriction, further information cannot be provided. The untreated RM materials were tested using a pH meter and showed to be high in alkaline (pH = 12) and considered too corrosive to be reused. Various neutralization methods have been used in the past to lower the pH value of untreated RM to a satisfactory level of pH = 9 or less. Brunori et al. (2005) and Johnston et al.

(2010) recommended a pH range of seven to nine for RM storage, transport, and future agricultural growth. In this study, the pH values of the RM specimens were reduced by mixing the untreated RM with (i) saline solutions and (ii) gypsum solutions. The saline solution was prepared by mixing tap water with non-iodized sodium chloride with a concentration of 35 g/L (close to the concentration of seawater). The saline solution was mixed with the untreated RM at a ratio of 20:1 (i.e., 1 kg of untreated RM mixed with 20 L of the saline solution), as Johnston et al. (2010) recommended. For the gypsum treatment, the solution was prepared at a ratio of 60 g gypsum mixed with 1 Kg of untreated RM per Glenister and Thornber (1985). Detailed RM treatment procedures were recorded in Machado (2020). The pH values were constantly monitored (Figure 2) for the three types of red mud (Untreated, Saline-treated, and Gypsum-treated). The pH values dropped from 12 to around 10 in a short period and gradually decreased over three months. When the treated RM reached a pH of 9 or lower, the solution was oven dried using a laboratory oven. Then, the RM was broken down into a dry powder to reconstitute simple shear test specimens. Three years after the original measurement, the pH values of the untreated and saline-treated RM stabilized at 8.5 to 9.75, and the gypsum-treated RM to a pH value of 7.6.

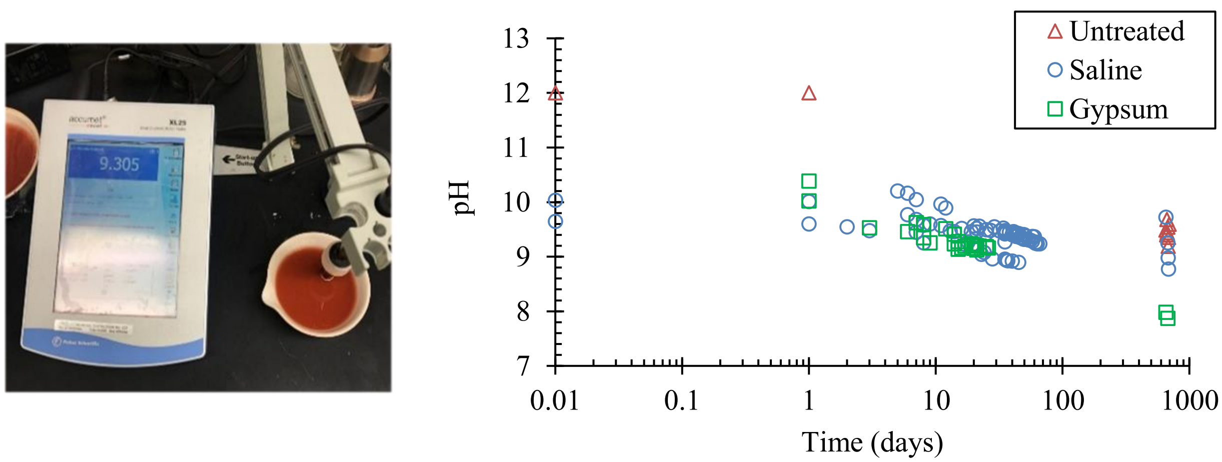

Figure 2. Testing RM pH value with a pH meter (left); pH Reduction Time History (right)

Minimum and maximum index density tests were performed. The maximum index density tests were performed according to (ASTM D4253-00), using a vibratory table set for vibration. The minimum index density tests were performed in accordance with (ASTM D 4254-00). Table 1 summarizes the density test results and shows that the RM treatments would generally lower minimum density by 7% and maximum density by 2%.

Table 1. Summary of Index Density Test Results

Red Mud Type	Minimum Density (ρ_{dmin}) [kg·m^{-3}]	Maximum Density (ρ_{dmax}) [kg·m^{-3}]
Untreated	1,072.1	1,701.3
Saline-Treated	981.1	1,673.5
Gypsum-Treated	1,000.8	1,664.1

Cyclic Simple Shear Test

Cyclic simple shear tests were carried out to understand the dynamic properties of red mud. Thirteen dry uni-directional cyclic simple shear tests were performed according to (ASTM D8296-19). Simple shear specimens were reconstituted from the oven-dried RM using the dry pluviation method (Kwan and El Mohtar 2020) to a nominal 65 mm diameter and an average 22 mm height (Figure 3). The samples were reconstituted as medium-dense (55 - 66% relative density with an average of 61%). Considering the silty-clay behavior of RM, specimens were consolidated to 200 kPa using incremental loading in three stages: 50, 100, and 200 kPa to avoid failure from a sudden stress increase. After reaching the targeted vertical stress for each consolidation step, the vertical load was maintained until no further deformation was recorded from the local LVDT. Our results show that RM is a highly compressible soil, according to Kulhawy and Mayne (1990), with an average compression index of 0.63, falling within the compressibility range (0.4-1.2) of San Francisco Bay mud (Holtz et al. 2011). After being consolidated to 200 kPa, the average relative density for the 13 tests reached 78 %, which is dense consistency. The average post-consolidation relative density of the three types of RM is consistent, being 77.2% for untreated, 79.7% for saline-treated, and 77.7% for gypsum-treated. Table 2 shows the pre and post-consolidation relative density of each of the 13 tests. The shearing phase was conducted under cyclic loading generated by a uni-directional harmonic cyclic motion under load control. The specimen heights were commanded to be stationary to simulate undrained conditions (i.e., active height control to achieve constant volume). The CMDSS device was capable of maintaining the vertical strain below 0.05% during the cyclic loading, except for test RMS1, where the axial strain reached 0.1% during the cyclic stage.

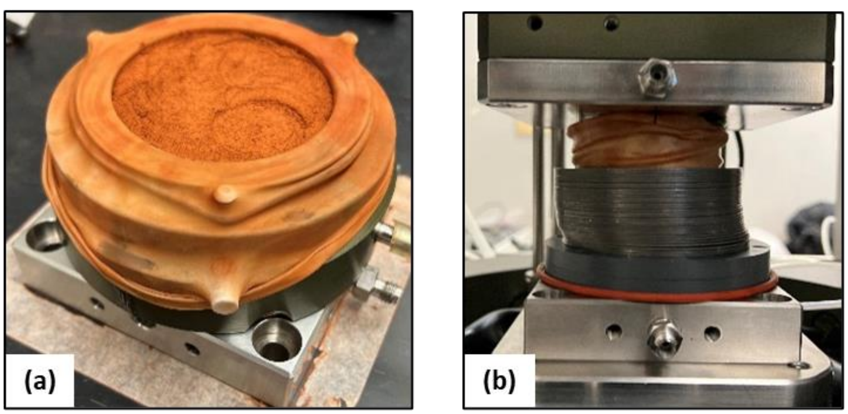

Figure 3. Reconstituted CSS test specimen (a) after pluviation and (b) during shear testing

TEST RESULTS

Table 2 summaries the results of the 13 CSS tests, including the number of cycles for each test reaching liquefaction initiation with various definitions: 1) excess pore pressure ratio, r_u, reaching 95%; 2) r_u reaching 100%; 3) induced shear strain, γ, reaching 3% single amplitude; and 4) γ, reaching 6% double amplitude. The Committee on Soil Dynamics of the Geotechnical Engineering Division (1978) defines liquefaction as the phenomenon in which saturated cohesionless soils suffer a transformation from solid to liquid state due to a significant decrease in the strength as a consequence of excessive pore pressure generation during a rapid dynamic loading. Wu et al. (2004) investigated different commonly used failure criteria for liquefaction in laboratory testing. Their study concluded that the 6% double amplitude shear strain criterion is proportional to a r_u value of 0.95 in the pore pressure ratio criterion, with r_u values as low as 0.8 for very dense materials. Ishihara (1993) recommends 3% to 3.5% simple amplitude shear strain. For our RM test results, some tests with low Cyclic Stress Ratio (CSR) values did not reach 100% r_u and 6% DA despite a few hundred cycles of small amplitude loading. Therefore, this investigation adopted the criteria of ru value reaching 0.95 and SA = 3% as the liquefaction triggering criteria to perform two independent analyses and present results from both analyses. Figure 4 shows the example stress-strain and stress-path from one of the gypsum-treated tests (RMG4). Aiming to show RM dynamic behavior relative to clean cohesionless materials, Figure 5 shows the excess pore pressure development of the 12 RM tests (excluding test RMU2, which has almost a thousand cycles), compared with simple shear test results on clean Monterey Sand reported by De Alba et al. (1976). Monterey sand is characterized by its angularity, which is commonly used in liquefaction investigations, such as the one from Wu et al. (2004). Figure 5 shows that the excess pore pressure developments of the three types of RM are similar. Both Figure 4 and Figure 5 introduce the time of the cyclic stage using a color scheme, going from the beginning of the stage in dark blue to the end in dark red.

Table 2. Summary of RM Cyclic Simple Shear Tests

Red Mud		Relative Density (%)		Cyclic Stress Ratio (CSR)	N_f			
ID	Type	Before	After Consol.		r_u (95%)	r_u (100%)	SA = 3%	DA = +6%
RMU1	Untreated	59.31	82.79	0.21	2.61	-	0.76	8.3
RMU2		57.46	77.39	0.16	997.61	-	995.23	-
RMU3		55.77	75.58	0.21	4.13	-	1.79	28.8
RMU4		57.83	74.1	0.19	11.58	14.61	8.73	93.2
RMU5		56.75	76	0.2	2.6	-	1.21	14
RMS1	Saline	60.65	80.68	0.18	4.07	-	2.17	23.8
RMS2		61.21	76.98	0.22	1.05	1.57	0.34	8.7
RMS3		63.03	80.54	0.166	15.08	-	13.26	138.8
RMS4		64.39	80.74	0.15	51.04	58.09	48.23	504.5
RMG1	Gypsum	60.31	75.98	0.16	66.54	69.57	63.75	662.4
RMG2		63.63	79.12	0.19	4.08	5.12	2.74	28.7
RMG3		63.11	77.49	0.21	2.06	3.08	1.24	13.8
RMG4		65.82	78.36	0.18	7.55	9.58	6.69	68

The cyclic simple shear tests were used to develop the liquefaction capacity curves, which can reflect the liquefaction resistance of each type of RM. Figures 6a and 6b show the results of the two different liquefaction initiation criteria along with the power fitting formula:

$$CRR = a * N_f^{-b}$$

where CRR = Cyclic Resistance Ratio; N_f is the number of cycles for liquefaction initiation; and a and b are curve fitting parameters. The a and b parameters are shown in Figures 6a and 6b.

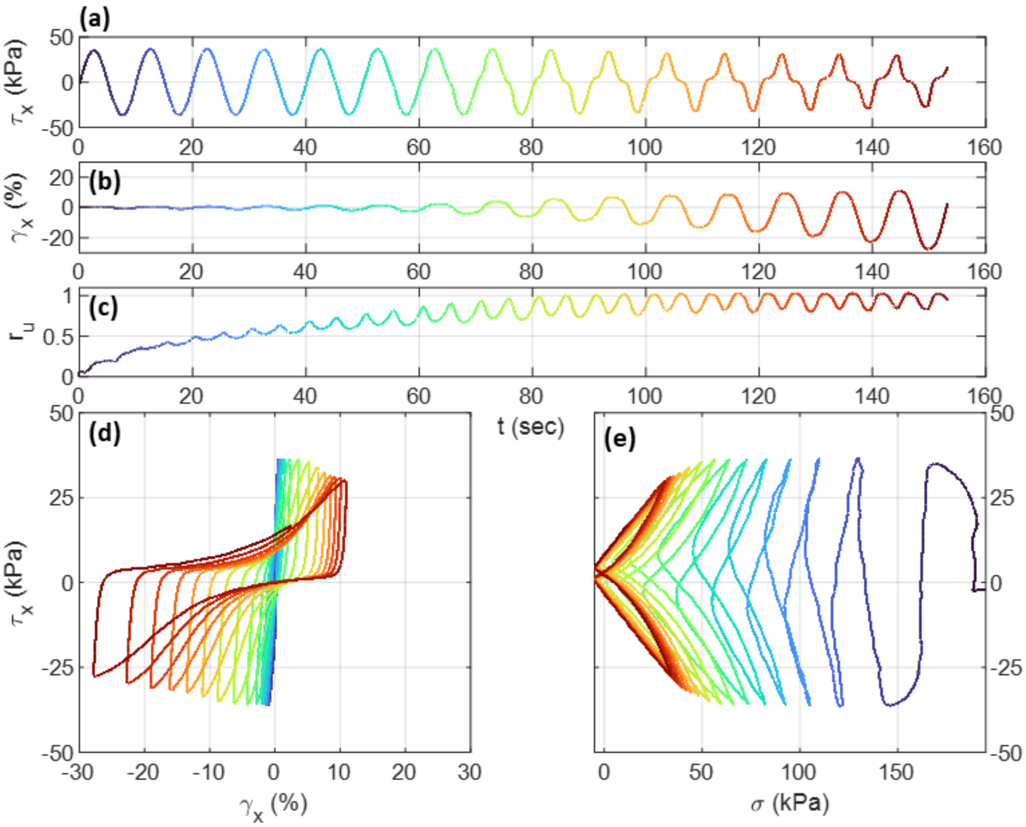

Figure 4. Example Test Result (RMG4). (a) Stress vs. Time; (b) Shear Strain vs. Time; (c) Excess Pore Pressure Ratio vs. Time; (d) Stress-Strain; and (e) Stress Path

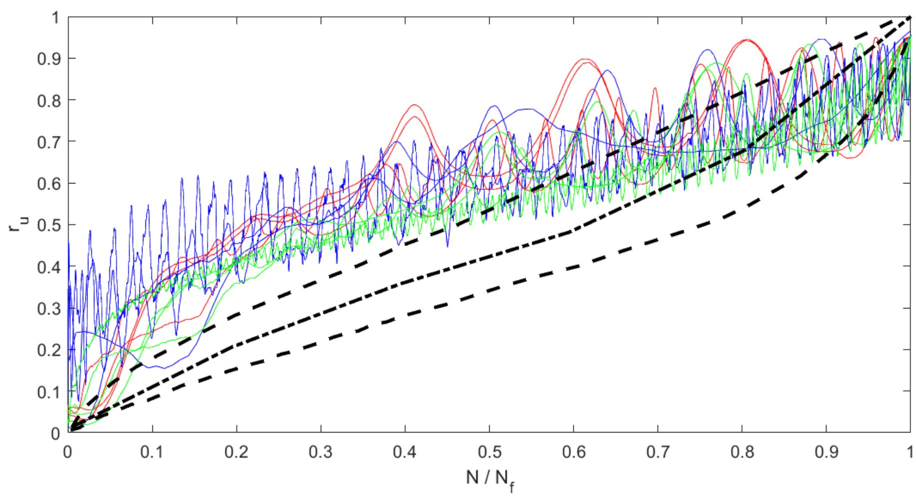

Figure 5. r_u development for the 12 CSS tests. Red = Untreated tests; Blue = Saline-treated; Green = Gypsum-treated. Black lines are ranges reported by (De Alba et al. 1976), tested on Clean Monterey Sands.

Parameter b represents the slope of a liquefaction capacity curve. The greater the absolute value of b, the flatter the capacity curve, meaning a minor liquefaction resistance to the high-amplitude cyclic loading but higher resistance to the low-amplitude ones. Boulanger and Idriss (2007) report b = 0.337 for clean sand and b = 0.135 for clay, and Romero (1995) documented that the value can be as low as 0.073 for aggregate tailings slime, an ML material. Comparing the three different types of Red Mud that were tested, the order of liquefaction resistances, from the greatest to the lowest, is the following: (1) Untreated, (2) treated with gypsum solution, and (3) treated with saline solution (Figures 6a and 6b). The results show that RM treatments for reducing pH values would reduce liquefaction resistance. Out of the two methods, specimens treated with gypsum demonstrate a relatively less strength reduction than the saline specimens, while both reached a desired pH range. Seed et al. (1975) proposed that the equivalent number of uniform stress cycles for a 7.5 magnitude earthquake is 20. Therefore, considering the $r_u = 0.95$ liquefaction triggering criteria, the CRR of untreated red mud to withstand a 7.5 magnitude is 0.19, whereas 0.162 (15% reduction) for treated with salt solution and 0.172 (9% reduction) for treated with gypsum solution.

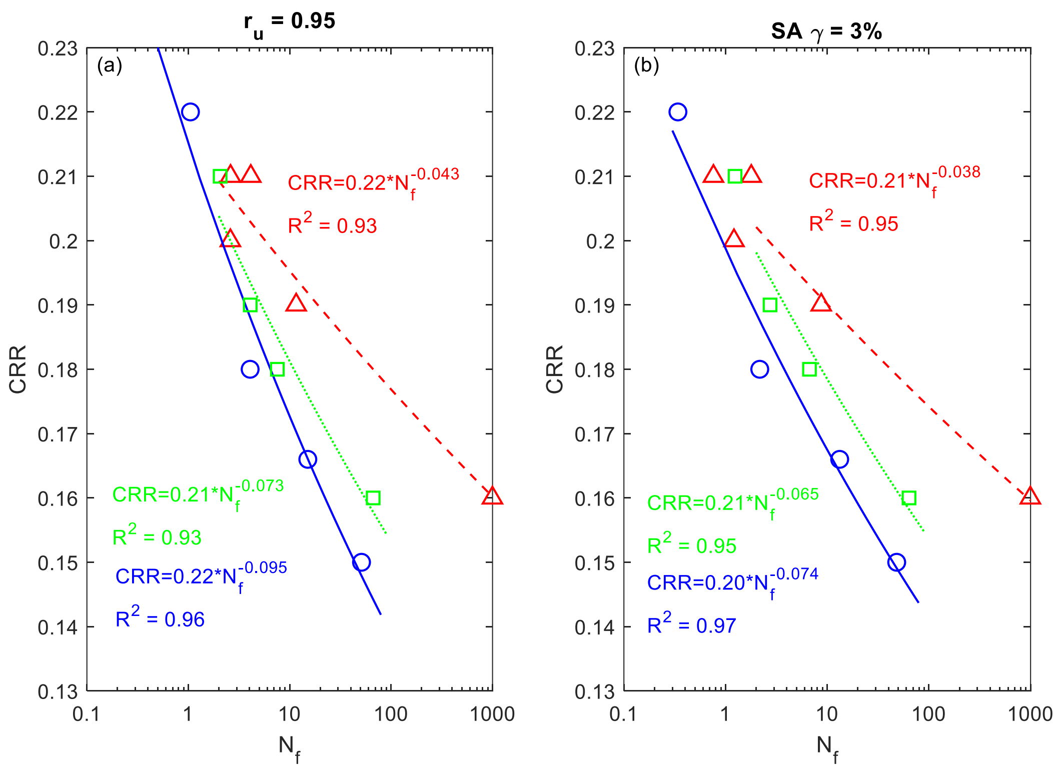

Figure 6. Cyclic Resistance Curves for (a) Excess Pore Pressure Ratio & (b) Shear Strain Assessments. Red = Untreated tests; Blue = Saline-treated; Green = Gypsum-treated

CONCLUSION

This study performed cyclic simple shear tests to investigate and compare the dynamic characteristics of untreated bauxite and bauxite residue treated by two neutralization methods: (i) mixing with saline solution and (ii) gypsum solution. The results show that the cyclic resistance of untreated samples is the highest in terms of liquefaction capacity curves but with the flattest slope and about 10% more CRR than the treated red mud per Seed et al. (1975) criteria for a 7.5 magnitude earthquake. Meanwhile, the treated red mud demonstrated lower liquefaction resistance, with saline-treated being weaker than gypsum-treated.

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